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Civil Application of Differential GPS Using a Single Channel Sequential Receiver

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ABSTRACT

GPS has the potential of satisfying worldwide and local civil navigation requirements for Area Navigation (RNAV), Landings and Takeoffs under minimum ceilings and Advanced Air Traffic Control (ATC) Operations. Use of GPS in a differential mode in local areas is key to full achievement of this potential.

The report describes the GPS system and its status; discusses GPS signal availability for the civil community; defines alternative differential GPS concepts; shows predicted performance enhancement achievable with differential GPS and the operational improvements which will result; and outlines a development program to test and evaluate differential GPS concepts, performance and operational procedures applicable to helicopters.

This report was prepared primarily to identify potential benefits which will be derived from helicopter use of GPS in the differential mode. Fixed wing aircraft will receive significant benefits from differential GPS, but the fixed wing application is not addressed explicitly in this report.

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SECTION 1

INTRODUCTION AND SUMMARY

1.1 BACKGROUND

GPS is a satellite-based, radio navigation system designed to provide global, all weather, 24-hour, highly accurate 3-D navigation and time to an unlimited number of users. It is under development by the U.S. Department of Defense (DoD) and is scheduled to become fully operational by 1987. In the meantime, a few GPS satellites provide worldwide signal coverage a few hours each day for test and development purposes as well as for any operational missions that can be scheduled in conjunction with the availability of the GPS signals. Appendix A describes the GPS system, its status, and the successful field tests which have been conducted during the advanced development phase of the program.

As indicated in Appendix A, three types of GPS information are transmitted: a Precision (P) Code signal; a Coarse Acquisition (C/A) Code signal; and a navigation message. The P and C/A Code signals are pseudorandom digital sequences modulated on a UHF carrier and used for ranging. The navigation message, also modulated on the carrier, contains satellite position, time, and atmospheric propagation data. The P Code is a high frequency (10 MHz) modulation providing navigation accuracy in each axis on the order of 10 meters, RMS, and is intended exclusively for U.S. Military and DoD authorized users. It is transmitted on each of two UHF frequencies for ionospheric correction purposes. The C/A Code is a low frequency (1 MHz)

modulation providing navigation accuracy in each axis on the order of 15 meters, RMS, and is intended to aid in acquisition of the P Code and for civil navigation. It is modulated in quadrature with the P Code and transmitted on the higher of the two UHF frequencies. C/A Code users apply ionospheric corrections based on the atmospheric data in the navigation message.

P Code and C/A Code performance was validated in Phase I testing. C/A Code performance was much better than anticipated prompting a DoD decision to incorporate in operational satellites a capability to degrade C/A Code performance selectively to a "worst case" position accuracy of 200 meters, CEP. DoD has indicated that this C/A Code degradation will be relaxed with time commensurate with national security interests. No timetable for DoD relaxation of degraded signal constraints has been announced.

The need to provide better accuracy for precision landings than available from either the P or C/A Code spurred interest in the concept of differential GPS navigation. At the same time, this technique is of interest because it may ameliorate the effects of degraded C/A Code performance in local areas.[1]

Accordingly, the Aircraft Guidance and Navigation Branch, NASA, Ames Research Center (ARC) sponsored this study to document the need for differential GPS and outline a test program to investigate the utility of differential GPS, especially as applied to helicopters. Fixed wing benefits derived from differential GPS, while similar, are addressed only incidentally in the study.

1.2 DIFFERENTIAL GPS CONCEPTS

Differential navigation is currently in use with Omega, Loran-C and the TRANSIT satellite system. The differential technique achieves substantial improvement in

position accuracy by transmitting corrections from a calibration site to users in the vicinity who apply the corrections to cancel errors common to the locale. In this technique, a receiver located on a surveyed point selected as the reference or calibration site for the locale continuously determines errors present in received navigation signals by comparing computed position with the known coordinates of the calibration site. The difference between computed and known position represents the navigation error which is typically highly correlated for all users in the vicinity of the calibration site. The error generally varies slowly relative to the time required to transmit corrections from the calibration site to nearby users who apply the corrections to improve their position solutions. For Omega, Loran-C and Transit, the technique provides substantially improved positions over distances up to a few hundred miles.

The differential techniques is applicable to GPS navigation, and Figure 1-1 illustrates one type of differential GPS concept.[2] In this concept a GPS receiver is located on a surveyed point where X, Y, Z position errors or individual satellite range errors can be identified and corrections determined. These corrections are transmitted on a VHF data link to aircraft which operate in the same area and which are, therefore, subject to the same errors. The corrections obtained from the reference receiver are used to improve the position and velocity accuracy of the airborne GPS receiver solution.

Other concepts include transmitting corrections on a GPS signal generated at and transmitted from the reference site (pseudolite concept) or transponding (i.e., receiving and retransmitting on a different frequency without processing) GPS signals from the reference site (translator concept). These concepts are described in this report along with variations possible in correction algorithms and satellite selection techniques.

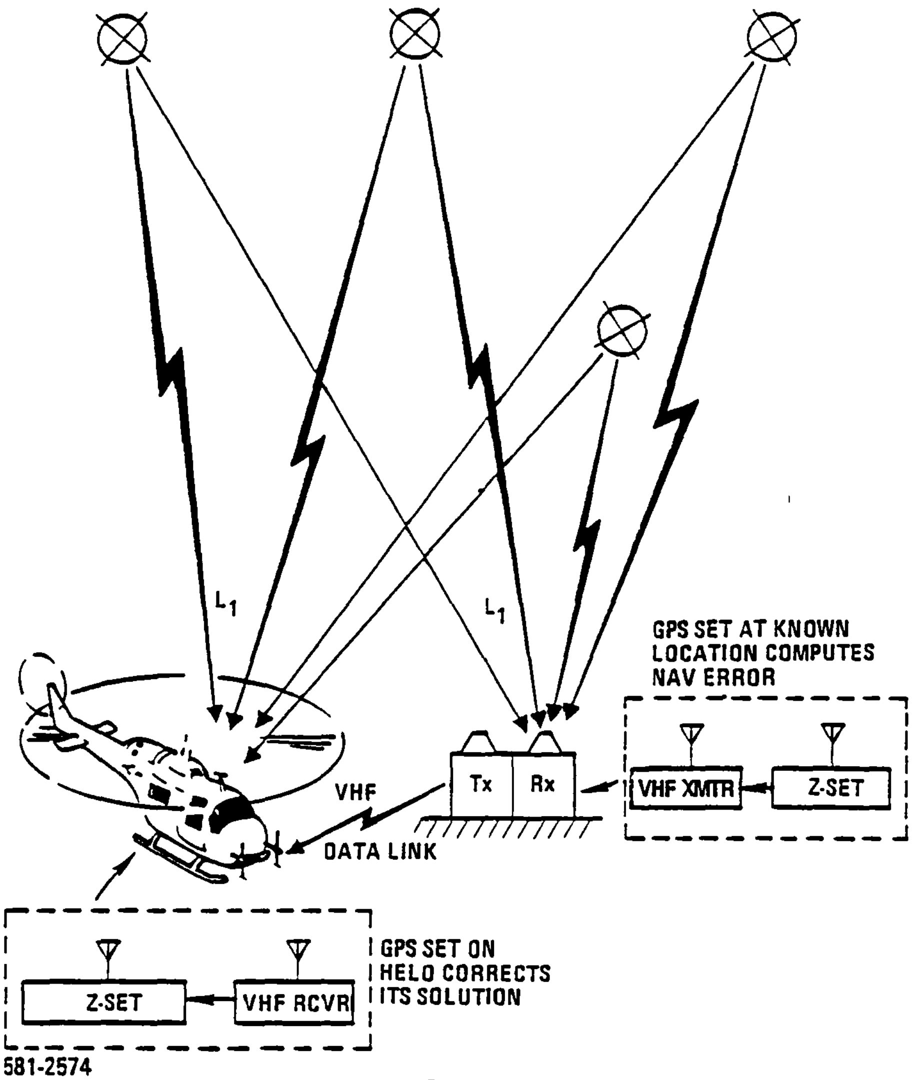

Figure 1-1. Differential GPS Navigation

1.3 DIFFERENTIAL GPS PERFORMANCE

Calculations performed in this study indicate that single channel P Code receivers have the potential in the differential mode to provide navigation accuracies on the order of 2.5 meters, 2σ, in each axis. This type of navigation performance would qualify for Category I approaches and landings per current FAA specifications and warrants consideration for Category II and III operations.

Study results also indicate that single channel C/A Code receivers as presently designed would provide navigation accuracies in the differential mode on the order of 10 meters, 2σ, in each axis. This type of navigation accuracy would not qualify for Category I approaches and landings under current FAA navigation standards. However, differential C/A Code performance sufficient for Category I and, perhaps Category II and III operations is projected for C/A Code sets optimized for the approach and landing environment, particularly if FAA navigation standards can be broadened for selected applications, such as helicopter service. In this vein, a review is recommended of FAA navigation accuracy requirements relative to both GPS characteristics and aircraft with slow speed landing capability, such as helicopters and VTOL aircraft.

The calculations also indicate that differential performance in local areas with intentionally degraded C/A Code signals is potentially comparable to that with unperturbed C/A Code signals. Relative accuracy between aircraft in the same airspace would be similar without differential corrections, provided the same satellites were being tracked simultaneously. Thus, inherent relative GPS accuracy coupled with altimeter inputs has the potential to satisfy all enroute and terminal area navigation needs under degraded GPS signal conditions, and the differential technique would extend that potential to at least non-precision approaches and landings in a local area.

1.4 DIFFERENTIAL GPS COST

The extra costs associated with implementing a differential GPS capability in addition to a conventional GPS capability are (1) those incurred for changes or additions to conventional airborne GPS equipment and (2) those involved in the acquisition, installation, and operation of the ground calibration site. The extra cost

for airborne differential GPS equipment could range from less than 5% of the cost of a conventional C/A Code system up to as much as 50% depending on the availability of suitable data link receivers on participating aircraft and the type of differential concept employed. While the eventual cost of civil aviation GPS sets is difficult to predict at this time, a 1979 ARINC report concludes that they could be produced in quantity for under $5000 (1977 dollars). Ground equipment acquisition, installation, operation and maintenance costs would not be significant cost factors if amortized over 50 or more users per site. Differential GPS is, therefore, anticipated to be an affordable option.

1.5 THE NEED FOR A DIFFERENTIAL GPS TEST PROGRAM

The ideal aircraft navigation system would provide worldwide, all-weather, 24-hour continuous position and velocity data of sufficient accuracy for enroute navigation under congested conditions and for non-precision and precision approach and landing operations, all without dependence on a point or beacon reference navigation aid.[3] GPS with the addition of the differential mode is the only navigation system under development today with the potential of satisfying all of these requirements.

Differential GPS has the potential to permit effective use of the degraded C/A Code by the civil community for enroute, terminal area and non-precision approach and landing operations. It is also a relatively low cost, simple approach for extending precision approach and landing capability to a wide range of landing sites when degraded signal constraints are ultimately removed. This capability will facilitate accessibility to minimally equipped urban and remote airports and heliports which would benefit the commercial and general aviation community in general. It is of particular significance to helicopters if they are to maximize their utility and achieve their full growth potential by extending service to a virtually unlimited number of heliports.

A differential GPS T&E Program is, therefore, warranted to corroborate the predicted high accuracy achievable with differential GPS as well as its affordability and ability to mitigate degraded GPS signal effects. The test program should also investigate applicable display formats and operational procedures for differential GPS approach and landing operations. Relative accuracy attributes of conventional GPS can also be studied.

1.6 PROPOSED TEST AND EVALUATION (T&E) PROGRAM

A four-year program is recommended to develop and test differential GPS concepts and evaluate differential GPS performance for helicopter applications as part of the Aircraft Guidance and Navigation Branch's helicopter technology program.

FY 82	Evaluate candidate differential GPS concepts and prepare a detailed hardware/software specification for a differential GPS T&E System.
FY 83/84	Fabricate, assemble and checkout the differential GPS T&E System.
FY 85	Install and operate the differential GPS T&E System to evaluate differential GPS performance and operational procedures for helicopter applications.

Estimated program costs, exclusive of NASA supplied effort, approximate $2.5 million for the four-year effort depending on the extent to which the program considers alternate concepts, alternate displays and operating procedures. Completion of the T&E effort in FY 85 will provide needed data for timely development of an operational differential GPS capability relative to the scheduled deployment of the operational GPS space segment.

SECTION 2

PERFORMANCE AND OPERATIONAL IMPROVEMENT POTENTIAL OF DIFFERENTIAL GPS

2.1 GPS SIGNAL AVAILABILITY TO CIVIL USERS

The C/A Code is intended for use by the civil community. For national security reasons, DoD plans to provide the C/A signal in accordance with the following policy as stated in the Federal Radionavigation Plan (FRP):[4]

> "United States Radionavigation Policy (is) to make NAVSTAR GPS continuously available on an international basis for civil and commercial use at the highest level of accuracy consistent with national security interests. It is presently projected that an accuracy of 200M Circular Error Probable (CEP) (500M 2 drms) will be made available during the first year of full NAVSTAR GPS operation with accuracy available to civil users improving as time passes."

The FRP defines a 2 drms value as the radius of a circle which contains 95% of all possible fixes.

No timetable is specified for improving the accuracy but presumably it is tied to the advance of technology such that the undegraded C/A Code will be supplied when comparable worldwide navigation accuracy is available from sources other than GPS. At that time the C/A Code can be expected to provide an accuracy of 15 meters, RMS 1σ, in each axis (16 meters CEP).

The P Code is not intended for civil use, but it, too, will presumably be made available when comparable worldwide navigation accuracy is available from sources other than GPS. Because of its higher accuracy, P Code availability to the civil community can be expected to lag somewhat the availability of the undegraded C/A Code.

Thus, unless stated policy is changed in the interim, the civil community should expect to operate with degraded C/A Code signals for at least the first few years after GPS becomes operational. In the case of TRANSIT, the system became operational in 1964 and was released for worldwide commercial use in 1967. Whether GPS restrictions will be relaxed as quickly is questionable, but the precedent clearly suggests that full availability will emerge in the foreseeable future.

Both the inevitability of technology advance and the precedent set by the Navy Navigation Satellite (TRANSIT) System suggest that the full capability of the C/A Code and P Code will ultimately be made available without restriction. Accordingly, the justification for a GPS T&E program lies not only in differential GPS's potential to mitigate the effects of early C/A Code degradation but also in its ability to extend unrestricted GPS performance to precision terminal area operations cost effectively.

2.2 DIFFERENTIAL GPS NAVIGATION PERFORMANCE

2.2.1 CALCULATED PERFORMANCE

As indicated in Appendix A, extensive testing has been accomplished in over two years of Phase I field tests with 7 types of GPS user equipment on 11 host vehicles. Consequently, GPS system errors have been well documented and fall within specified limits as indicated in Figure 2-1.[5] These errors are allocated

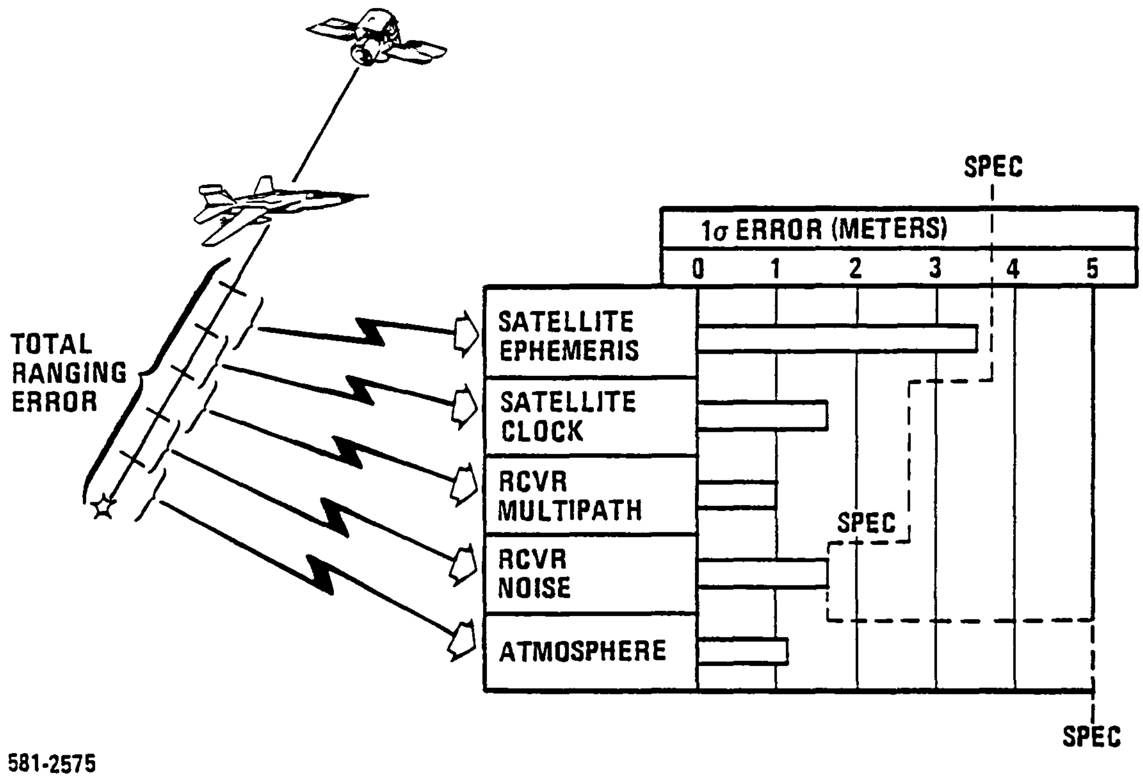

Figure 2-1. GPS System Error Budget Allocation - 1σ Field Test Results vs. Specification

to their appropriate bias or random category and their combined effect on position accuracy estimated in Table 2-1 for a P Code receiver. The Root-Mean-Square, RMS, value for the bias and random errors provides an estimate of a 1σ User Equivalent Range Error, UERE, to a satellite. Use of a filter, such as the Kalman filter used in GPS sets, substantially reduces the contribution of random errors to total error, particularly in steady or benign states. For purposes of illustration, the random error contribution to UERE is reduced by a factor of four in Table 2-1. This is a high level of filtering for sequencing sets which is considered attainable with a navigation filter optimized for the low dynamics approach and landing environment. In the simulations discussed in Section 2.2.2 better filter performance was achieved, as expected, for the multi-channel, non-sequencing sets modeled.

Table 2-1. Calculated 1σ Single Axis P-Code Accuracy

Error Source	Spec 1σ Error (Meters)			Field Test 1σ Error (Meters)		
	Bias	Random	Total	Bias	Random	Total
Ephemeris Data	3.7	0	3.7	3.5	0	3.5
Satellite Clock	2.6	0.7	2.7	1.5	0.7	1.7
Ionosphere	4.0	0	4.0	1.5	0	1.0
Troposphere	0	3.0	3.0	0	0.5	0.5
Multipath	0	2.8	2.8	0	1.0	1.0
Receiver	0	1.5	1.5	0	1.5	1.5
UERE (RMS)	6.0	4.2	7.5	3.7	2.0	4.2
Filtered UERE (RMS)	6.0	1.1	6.1	3.7	0.5	3.7
1σ Single Axis Error (DOP = 2.5)			~ 15			~ 9

Multiplying UERE by an appropriate Dilution of Precision (DOP) factor based on space segment geometry provides an estimate of the spatial, horizontal, or vertical position error which will result from the combined effects of ranging errors and system geometry. PDOP is the spatial (3-D) position DOP factor; HDOP is the horizontal (2-D) position DOP factor; and VDOP is the vertical (single axis) DOP factor. The statistical distribution of DOP factors is generally highly non-gaussian and varies with geographic location. For a discussion of the distribution of DOP values and its use in computing position error statistics see Reference 6.

Based on Reference 6 data, a single axis VDOP value of 2.5 multiplied by a 1σ UERE is used in this report to provide a conservative estimate of the 1σ vertical axis position error. It is also considered roughly representative of 1σ crosstrack, and

along track errors. For example, the 1σ single axis error for the Field Test P-Code case shown in Table 2-1 is estimated as follows:

$$1\sigma \text{ single axis error} = \text{VDOP} \sqrt{\text{Bias}^2 + \text{Filtered Random}^2}$$

$$= 2.5 \times 3.7 \text{ meters}$$

$$\sim 9 \text{ meters.}$$

Similar calculations using field test errors are summarized in Tables 2-2 and 2-3 for conventional and differential use of P Code, C/A Code, and degraded C/A Code signals. As shown in Table 2-2, the 1σ ionospheric error for the C/A Code in the conventional mode is assumed equal to the specification amount allocated to the bias category (i.e., 4 meters) since the accurate ionospheric correction applied in field tests by the two frequency P Code receivers is not available to single frequency C/A Code sets. Also, a 7.5 meter receiver noise is assumed in both modes for C/A Code code tracking sets based on in-house experience with the Magnavox Z-Set. In the case of degraded C/A Code performance calculations, an additional 80 meter hypothetical bias is included in the conventional mode as shown in Table 2-2 to illustrate the assumption that the 200 meter CEP performance intended for early civil GPS users (see Section 2.1) includes the effects of DOP. As indicated in Table 2-3, except for a small bias residual in the degraded C/A Code case, all bias errors are assumed cancelled in the differential mode. This is based on the premise that GPS geometry is essentially constant over large areas so that nearby users will experience and be able to cancel common errors. It is consistent with our experience in the TRANSIT satellite system. The small residual bias error included in the differential degraded C/A Code case is intended to illustrate that some effect of degradation may remain in the differential mode due to monitor station computational and data reporting delays. The extent of this effect has not been addressed in this study.

Table 2-2. Calculated 1σ Single Axis Accuracy, Conventional P-Code, C/A-Code, and Degraded C/A-Code

Error Source	Conventional P-Code 1σ Error (Meters)			Conventional C/A-Code 1σ Error (Meters)			Conventional Degraded C/A-Code 1σ Error (Meters)		
	Bias	Random	Total	Bias	Random	Total	Bias	Random	Total
Ephemeris Data	3.5	0	3.5	3.5	0	3.5	3.5	0	3.5
Satellite Clock	1.5	0.7	1.7	1.5	0.7	1.7	1.5	0.7	1.7
Ionosphere	1.0	0	1.0	4.0	0	4.0	4.0	0	4.0
Troposphere	0	0.5	0.5	0	0.5	0.5	0	0.5	0.5
Multipath	0	1.0	1.0	0	1.0	1.0	0	1.0	1.0
Receiver	0	1.5	1.5	0	7.5	7.5	0	7.5	7.5
Intentional Bias*	0	0	0	0	0	0	80	0	80
UERE (RMS)	3.7	2.0	4.2	5.5	7.6	9.4	80	7.6	80
Filtered UERE (RMS)	3.7	0.5	3.7	5.5	1.9	5.7	80	1.9	80
1σ Single Axis Error (VDOP- 2.5)			~9			~14			~200

*Hypothetical

Table 2-3. Calculated 1σ Single Axis Accuracy, Differential P-Code, C/A-Code, and Degraded C/A-Code

Error Source	Differential P-Code 1σ Error (Meters)			Differential C/A-Code 1σ Error (Meters)			Differential Degraded C/A-Code 1σ Error (Meters)		
	Bias	Random	Total	Bias	Random	Total	Bias	Random	Total
Ephemeris Data	0	0	0	0	0	0	0	0	0
Satellite Clock	0	0.7	0.7	0	0.7	0.7	0	0.7	0.7
Ionosphere	0	0	0	0	0	0	0	0	0
Troposphere	0	0.5	0.5	0	0.5	0.5	0	0.5	0.5
Multipath	0	1.0	1.0	0	1.0	1.0	0	1.0	1.0
Receiver	0	1.5	1.5	0	7.5	7.5	0	7.5	7.5
Intentional Bias*	0	0	0	0	0	0	3.0*	0	3.0
Calibration Site Residual	0	0.5	0.5	0	1.9	1.9	0	1.9	1.9
UERE (RMS)	0	2.1	2.1	0	7.9	7.9	3.0	7.9	8.0
Filtered UERE (RMS)	0	0.5	0.5	0	2.0	2.0	3.0	2.0	3.6
1σ Single Axis Error (VDOP- 2.5)			~1.3			~5.0			~9

*Assumed residual after differentially correcting for hypothetical intentional UERE bias of 80 meters.

For differential GPS calculations, an additional random error equal to the filtered random error is included as shown as an estimate of the residual error at the calibration site. In the case of differential performance with the degraded C/A Code, the results are illustrative only of the type of improvement which might result if use of the differential mode is technically compatible with the degradation techniques planned.

A comparison of Tables 2-2 and 2-3 clearly shows the substantial improvement provided by the differential techniques. Sections 2.2.2 and 2.2.3 substantiate the performance calculation in Tables 2-2 and 2-3, and Section 2.2.4 discusses the implications of the performance relative to current FAA navigation standards.

2.2.2 SIMULATIONS

In addition to the preceding GPS performance calculations, conventional and differential GPS performance with the P Code, C/A Code and degraded C/A Code was investigated in a digital computer simulation. Appendix B describes the simulation program and presents the results of the simulation. Simulation results show better performance than calculated in Section 2.2.1 due to the higher sampling rate and resultant improved filtering of the multi-channel, non-sequencing sets modeled.

In the simulation, a hypothetical noise model is included for the degraded C/A Code such that 200 meter CEP performance results. Thus, simulated degraded C/A Code performance in the conventional mode illustrates the navigation accuracy envelope the civil air community can anticipate in the first year of operational GPS use. Simulated degraded C/A Code performance in the differential mode and calculations in Section 2.2.1 assume a high degree of correlation between user and calibration site errors in local areas which may or may not be the case for the degradation technique

to be applied. Accordingly, the results of the differential simulations and calculations for the degraded C/A Code should be considered illustrative only of the best differential performance which can be expected from the degraded C/A Code in a local area.

2.2.3 FLIGHT TESTS

Extensive flight testing was conducted at Yuma, Arizona, during Phase I of the GPS program in conventional and differential modes using both the P Code and the C/A Code (Appendix A). In differential tests, differentially corrected P Code performance was better than three meters, RMS, in each axis with degraded GPS signals and PDOPS of 3 to 3.6 (corresponding conventional mode performance was on the order of 30 meters in each axis).[7]

Flight tests in the conventional (i.e., non-differential) mode with undegraded GPS signals produced accuracies comparable to those predicted by the calculations and simulations in this study. In the flight testing program numerous landings under Category I-type conditions were made by military helicopter pilots using conventional GPS. These results were achieved by proficient pilots, in well equipped aircraft, in good weather conditions (i.e., under conditions of minimum Flight Technical Error). Consequently, they are probably indicative of the best performance achievable with conventional GPS rather than of an inherent capability of conventional GPS to support Category I-type operations on a 2 sigma basis as required by FAA specifications. At the same time, the results also suggest that differential GPS with its substantially improved navigation accuracy relative to conventional GPS should accommodate at least Category I precision approaches and landings with either code.

2.2.4 DIFFERENTIAL PERFORMANCE VS. FAA NAVIGATION SYSTEM ACCURACY STANDARDS

2.2.4.1 Summary

Table 2-4 summarizes the results of the performance calculations in Section 2.2.1. 2σ values are shown to facilitate comparison with FAA navigation system accuracy standards shown in Table 2-5.[4]

Table 2-4. Calculated GPS Performance Summary

GPS Signal	2σ Single Axis Error (Meters), DOP = 2.5	
	Conventional Mode	Differential Mode
P Code	18	2.6
C/A Code	28	10
Degraded C/A Code*	400	18

*Hypothetical

Table 2-5. FAA Navigation System Accuracy Standards[4]

Operational Phase		Minimum Altitude (ft)	Accuracy (2 drms)	
			Lateral	Elevation
Enroute/Terminal		500	4 NM	500 M
Approach and Landing	Non-Precison	250	2 NM	100 M
	Precision Category I	100	±9.1 M*	±3 M*
	Precision Category II	50	±4.6 M*	±1.4 M*
	Precision Category III	0	±4.1 M*	±0.5 M*

*2σ

2.2.4.2 Differential Performance Implications

Differential P-Code performance of 2.6 meters, 2 σ, is predicted by the calculations and simulations. One of the significant sources of error in differential P-Code operation is receiver noise which is controllable to some degree by receiver design. However, P-Code receiver noise is roughly equivalent to each of the several other random error sources in differential GPS, so its substantial reduction, if possible, would not materially reduce the total RMS error. Thus, a differential P-Code accuracy of 2.6 meters, 2σ, probably approximates the "best" real-time differential GPS accuracy achieveable in a practical sense for moving vehicles with moderate dynamics.

Differential C/A Code performance of 10 meters, 2σ, predicted by the calculations and simulations does not approach the accuracy of the differential P-Code nor the "best" which should be achievable with the differential C/A Code. The C/A Code receiver model on which the prediction was based was designed for conventional mode navigation on aircraft with moderate flight dynamics. It contains a substantial receiver noise component which is not of particular concern in the intended application because, when filtered, receiver noise is not a significant error compared with bias errors. In the differential mode, however, bias errors are cancelled, and the level of receiver noise modeled becomes the dominant random error obscuring, in effect, other random errors encountered. Thus, to improve differential C/A Code performance, requires substantial reduction in C/A Code receiver noise.

Several software techniques which would have little, if any, impact on cost are available to reduce receiver noise effects in the approach and landing environment including optimization of tracking loops, doppler aiding, navigation filters and satellite sequencing rates for the relatively low dynamics approach mode. These

techniques are expected to reduce the error due to receiver noise by a factor of 2 or 3 relative to that shown by the calculations and simulations. This reduction would substantially diminish the dominance of the receiver noise effect in the differential mode.

Hardware techniques could also be used to reduce receiver noise contribution but would increase cost. These hardware techniques would include use of multiple channels and IMU and altimeter aiding.

Reducing C/A Code receiver noise to the point where it no longer obscures the other random error sources would produce performance which approaches P-Code differential performance and is key to achieving maximum differential mode accuracy from the C/A Code. Differential performance improvement versus cost impact for the applicable techniques should be investigated in subsequent studies.

2.2.4.3 FAA Navigation Accuracy Standards Review

A comparison of predicted differential GPS performance in Table 2-4 with current FAA navigation system accuracies listed in Table 2-5, indicates that differential P-Code sets (and, as indicated above, optimized differential C/A Code sets) should satisfy Category I requirements and meet horizontal navigation accuracy requirements for Category II and III operations but not vertical requirements. However, differential GPS vertical accuracy is very close to the stringent FAA vertical accuracy requirements for Category II and III operations, and a review of these requirements relative to differential GPS characteristics seems warranted, particularly for helicopters, for several reasons:

1. Total error is the RMS combination of navigation system error and flight technical error. Since flight technical error is generally the larger

error, a slight relaxation of the FAA vertical accuracy requirement (which would permit differential GPS to qualify for Category II and III operations) should not result in a significant increase in the total error budget.

2. The helicopter-unique capability to hover should permit helicopters to use predicted differential GPS vertical accuracies effectively in Category II and III conditions, e.g., one approach would be to fly to a hover at coordinates slightly above touchdown coordinates (by an amount equal, perhaps, to the GPS 2σ vertical position error applicable at that time) and then, based on accurate GPS velocity inputs, let down slowly to a soft landing. Radio altimeter aiding would greatly facilitate this operation.

3. Three unique GPS characteristics permit display formats to be utilized which will be of significant aid to a pilot in conducting Category II and III approaches and landings. First, GPS provides a linear measurement of track displacement rather than VOR/DME and ILS/MLS angular-type measurements, and full scale indicator deflections in the vertical and horizontal axes represent a selected fixed distance off course in the vertical and cross track direction, respectively. Second, since accurate 3-D position is known continuously, GPS sets can continuously compute the allowable deviation from selected course per FAA standards based on distance from TDZ. These two characteristics can be combined to provide the pilot with a readily comprehended display of current distance off course and, by continuously superimposing on the display the allowable deviation from course for the current position, a readily comprehended display of safety margin. The third characteristic, continuous knowledge of DOP conditions, can add

to the precision of pilot assessment of safety margin. For instance, a GPS set can compute the 1σ, 2σ or 3σ value for estimated position, and it can be displayed in bar form about the estimated position. In this way, the display could indicate the probability that current estimated position was within the allowable deviation from selected course for that position.

The above factors suggest that differential GPS accuracies may be suitable not only for Category I conditions but also for Category II and III applications, particularly for helicopters. Thus, a review of FAA navigation accuracy standards should be conducted in conjunction with flight tests to determine the extent to which the standards should be revised, if at all, to take maximum advantage of differential GPS for precision approaches and landings for various classes of aircraft and applications.

2.2.5 CONCLUSIONS

1. Both the C/A Code and P-Code will readily support non-precision approach and landing operations as specified for RNAV/IFR conditions.

2. Differential GPS improves performance of the P-Code to an extent that it should support precision approach and landing operations through Category I conditions and could conceivably support Category II and III operations, particularly for helicopters. C/A code sets will have to be optimized for the differential mode to achieve similar performance. The cost impact of optimizing C/A Code sets for differential operation should be investigated in subsequent studies.

3. FAA navigation accuracy standards should be reviewed in light of differential GPS characteristics to ensure that maxmum advantage is derived

from differential GPS for precision approaches and landings; e.g., knowledge of DOP conditions will assist in determining approach limitations, and helicopter hover attributes may permit standards to be broadened.

4. Provided differential methods are technically feasible with the degradation techniques to be applied, differential GPS has the potential to extend civil use of the degraded C/A Code signal in a local area to at least non-precision approaches and landings as defined for RNAV/IFR operations.

5. Provided differential methods are technically feasible with the degradation technique applied, relative navigation with the degraded C/A Code should also be feasible and provide relative accuracy for aircraft in the same air space which is comparable to differential accuracy. In this case, with an altimeter input the degraded C/A code would be suitable for all enroute and terminal area navigation needs.

2.3 DIFFERENTIAL GPS OPERATIONAL IMPROVEMENTS

From an operational civil aviation point of view, GPS should be considered as an Area Navigation (RNAV) system. The Federal Aviation Administration's (FAA's) Advisory Circular (AC) 90-45A (in process of being updated) sets forth basic considerations involved in introducing RNAV into the National Aviation System (NAS). At present the great majority of the RNAV systems in use are based on VOR/DME (VORTAC) inputs.

Other navigation systems which currently may be considered to have RNAV capability include Loran-C, VLF/Omega and INS/Doppler. These systems may be approved by the FAA for Instrument Flight Rules (IFR) operation enroute, in terminal areas and for

instrument approaches provided they equal or exceed the VOR/DME RNAV accuracies as specified in AC 90-45A. So far, none of these other RNAV systems has been approved by the FAA as a primary IFR RNAV System in all three modes.

Because of the angular divergence of the VOR radials, RNAV route widths may be in excess of 4.0 nm on either side of the route centerline in an angular splay, depending upon distance from the reference VORTAC (VOR/DME) facility. Inasmuch as VOR/DME facilities are subject to line-of-sight (radio horizon) limitations and in view of the decreasing accuracy of the VOR/DME signals in relation to distance from the facility, RNAV instrument approaches are not authorized at locations more than 25 nm from a VORTAC station.

Further limitations of the VOR/DME RNAV system are lack of coverage on a fully national basis, especially in remote areas and offshore, and lack of adequate inputs for low altitude navigation except when in the immediate vicinity of a VORTAC facility. Even with the relatively low number of VOR/DME RNAV instrument approaches currently possible, a large percentage of these are not under radar surveillance, thus greatly limiting the frequency of approaches acceptable to ATC.

Under the best of conditions, RNAV instrument approach minimums generally are not less than MDA (Minimum Descent Altitude) 400 ft and visibility 6000 ft. Helicopter visibility minimums may be half of those approved for fixed wing aircraft instrument approaches. All RNAV instrument approaches are classified as "non precision". A "precision" approach according to current FFA definition can only be made with an ILS (or future MLS) or a precision approach radar (PAR/GCA) at the point of intended landing. A Category I precision instrument approach facility provides minimums down to 200 ft Decision Height (DH) and 3000 ft Runway Visual Range (RVR); Category II, 100 ft DH and 1200 ft RVR; and Category III in three visibility gradations down to 0-0.

There are three basic categories of RNAV systems:

1. 2-D - Whereby the pilot may determine his cross-track and along-track position (x-y coordinates).
2. 3-D - Whereby the pilot may determine his x-y coordinates plus his z (altitude) coordinate in relation to a desired vertical profile (also referred to as "VNAV").
3. 4-D - Whereby the pilot has the ability to arrive precisely at a point in space at a desired altitude on a desired track and at a desired time (x-y-z-t) coordinates. 4-D RNAV also permits arrival at a desired touch down zone (TDZ) on an airport or heliport at a desired time.

Currently, most general aviation RNAV systems in use are 2-D. Airline systems generally are 3-D. 4-D systems are still in development, but it is doubtful that they can be made acceptably accurate using the VOR/DME sensors (delivery accuracy goal is ±5 seconds).

In the present NAS, precision approach capability is provided at only about 500 civil airports and yet there are over 13,000 public service airports and heliports in the United States and its possessions. In addition to general aviation's needs for "precision" instrument approach capability at thousands of conventional airports, there are even greater instrument approach "precision" capability requirements when considering the growing need for instrument approaches to virtually an unlimited number of landing/takeoff areas for IFR-capable helicopters and other VTOL's (vertical takeoff and landing vehicles) now being developed.

In view of the foregoing, a variety of important operational improvements can be identified which may be derived from the application of differential GPS. These improvements will accrue primarily in the so-called "terminal area" in fixed wing parlance, i.e., the approach/landing/takeoff environment including missed approaches and aborted takeoffs.

- Approach/Landing - A significant improvement resulting from differential GPS accuracy will be to achieve substantially lower ceiling and visibility minimums for helicopter approaches in Instrument Meteorological Conditions (IMC) than are possible with VOR/DME RNAV (or any other existing or planned RNAV system). Depending on the GPS signal access available, differential GPS would be expected to at least equal that of a Category I instrument approach facility (ILS or MLS).

  Because of the helicopter's inherent capability of being flown at low to zero speed to a hover, differential GPS has the potential to support 0/0 (Category III C) helicopter landings. Such operations, however, would require certain controls, displays, and procedural technique not currently available. For Category I and II approaches, on the other hand, the currently available HSI could be used along with standard IFR procedures.

  All of the operational advantages of ILS/MLS with colocated precision DME would be provided with differential GPS including multi-segment vertical flight paths for noise abatement and obstruction clearance; "curvilinear" approach paths; precision measurement of elevation independently of a baro or radio altimeter with constant computation of glide slope; and precise measurement of distance/time to TDZ. These capabilities will also facilitate helicopter constant decelerating approach profiles.

Another advantage of the high accuracy of differential GPS is to provide the helicopter pilot with the capability to follow narrow-width, discrete routings precisely so as to facilitate separation in terminal areas between helicopters and fixed wing traffic and to/from heliports at conventional fixed wing airports.

- Takeoff - As in the case of approaches, helicopter takeoffs in IMC conditions will require that the pilot precisely follow discrete, narrow width routes for purposes of obstruction clearance and noise abatement, as well as to facilitate separation from fixed wing aircraft where applicable. These are sometimes referred to as "SID's" (Standard Instrument Departures). The high accuracy of differential GPS will make operational improvements of this type feasible.

- Missed Approaches - Current FAA regulations specify that every instrument approach procedure (IAP) must have a missed approach procedure. According to FAA standards, a turning helicopter missed approach procedure requires a 1.3 nm turning radius. This takes up altogether too much airspace but is based on the assumption that the pilot does not have positive course guidance and, therefore, may drift considerably with cross winds. Airspace currently required for missed approach procedures can cause higher MDAs than otherwise necessary, can restrict discrete routing of helicopters with fixed wing traffic, and can cause the helicopter IAP to be performed at considerable distances from a desired landing area, (e.g., point-in-space approaches). In such approaches, the pilot, after reaching MDA must proceed by visual reference to the surface (helicopter special VFR) to his intended point of landing (which may be as far as 20 nm away).

The overall question of obstruction clearance for instrument approaches and departures is extremely complicated. Criteria are set forth in detail in FAA "TERPS" Manual 8260.38. However, this manual is by no means up to date or complete. Continuing work on this manual will be needed, including such matters as provision for the application of differential GPS RNAV.

Like missed approach procedures, helicopter holding procedures require the protection of too much airspace (5-6 nm laterally and longitudinally). In a controlled situation, a helicopter can hold at the standard turning rate of 3° per second, at 90 kts, with a 3,000 ft turning radius. Under present FAA criteria, IAP's must include a holding procedure, with few exceptions.

Differential GPS, with the pilot using a standard HSI display, would provide the positive guidance necessary to follow precisely defined tracks and elevations so as to avoid obstructions, thus greatly reducing the airspace required in the current TERPS criteria applicable to helicopter missed approach procedures. The same principles apply to reducing airspace requirements for helicopter holding patterns.

However, the high navigation accuracy to be derived from differential GPS should make helicopter missed approaches a rarity. When using differential GPS 4-D RNAV for approaches, the pilot will be able to control the speed of his helicopter so as to arrive at the TDZ precisely at the time specified by ATC, thus minimizing the need for holding and holding patterns.

- <u>Aborted Takeoffs</u> - An aborted helicopter takeoff generally is caused by partial or total power failure. With today's IFR helicopters, most of

which have two or three turbine power plants, the safety of an aborted takeoff (after being airborne) would be greatly enhanced by the pilots having the ability to quickly and precisely return to TDZ through the use of differential GPS.

- ATC Improvements - As indicated in the foregoing, many helicopter operational improvements may be derived in the landing/takeoff environment through the application of differential GPS navigation accuracy. These improvements, in turn, could lead to operational improvements in Air Traffic Control. In environments where ATC has control of the airspace, the high accuracy differential GPS x-y-z coordinates of the helicopter's RNAV system could be transmitted via data link (DABS or other) to the ATC facility to supplement or be in lieu of radar surveillance. In other instances, where ATC coverage is not available, air-to-air exchange of x-y-z coordinates derived from the airborne 3-D RNAV system using differential GPS inputs would permit pilots to exercise their own separation assurance. This capability would require the use of data link communication and a suitable cockpit display (sometimes referred to as a CDTI (Cockpit Display of Traffic Information). Even in ATC controlled airspace, however, pilot use of a cockpit separation assurance display would significantly assist in unloading the man-intensive heavy workload ground ATC system thus raising controller productivity. Using the high accuracy differential GPS inputs to a CDTI also would permit precise position comparison between helicopters and between helicopters and fixed wing aircraft, thus greatly increasing safety in terminal areas.

2.4 P-CODE CONVENTIONAL GPS ALTERNATIVE TO DIFFERENTIAL GPS

Several factors work against use of the P-Code in a conventional mode as an alternative to differential GPS:

1. Marginal improvement in civil air operations is provided relative to the C/A Code in conventional mode.

2. Less accuracy is achieved relative to differential GPS.

3. No cost advantage is obtained.

4. Less access is predicted.

P Code performance does not provide substantial improvements in civil air enroute or terminal area operations relative to the undegraded C/A Code nor provide the precision approach and landing potential of differential GPS (Section 2.2). This applies not only to a single-channel P-Code set but to multi-channel, aided sets as well. In the case of the multi-channel, aided set, its primary purpose is to ensure good performance in jamming conditions and high dynamics maneuvers which are military requirements of little significance to civil air.

Civil community access to the P-Code is expected to lag unrestricted C/A Code access, and widespread use of the P-Code by the civil air community is, therefore, not likely in the near term. Some use of P-Code sets in the differential post processing mode is anticipated ultimately for high precision operations, such as hydrographic surveys, side looking radar surveys and aerial photography; and use in the differential real time mode for precision approaches and landings may ultimately occur if P-Code sets become readily available and cost competitive.

SECTION 3

OPERATIONAL APPLICATIONS

3.1 DIFFERENTIAL GPS USES

As indicated in Section 2, the civil aviation community would derive great utility from two projected differential GPS capabilities:

1. Differential techniques may retrieve basic C/A Code navigation performance from degraded C/A Code signals locally so that approximately 10 meters position accuracy is provided in each axis, 1σ; and

2. Differential techniques should enhance undegraded GPS navigation accuracy to an extent that it would support Category I approaches and landings and possibly Category II and III operations, especially for helicopters.

The performance provided by the first listed differential GPS capability would permit localized civil use of degraded C/A Code signals for at least non-precision approaches and landings; comparable relative GPS performance coupled with altimeter inputs would satisfy all enroute and terminal area navigation needs. Thus, with differential GPS available during signal degradation periods, the civil air community could make use of GPS as an RNAV/IFR system for all enroute, terminal area and non-precision approach and landing operations; i.e., GPS use would be similar to current VOR/DME use with the added advantage of better accuracy and global coverage independent of beacon aids.

The second listed differential GPS capability would permit GPS to be used as a relatively low cost means to expand Category I capability to a virtually unlimited number of landing sites and possibly to support Category II and III operations for selected applications, locations and conditions. In this case, differential GPS use would be similar to ILS/MLS and PAR/GCA use; i.e., it would be used as follows:

- For all-weather approaches and landings.
- As an aid to reduce airspace requirements for missed approaches.
- As an aid to minimize missed approaches.
- As an aid to safety for an aborted takeoff by facilitating a rapid return to takeoff point as a result of precision navigation capability.
- As an aid (4-D) to minimize the need for holding.
- For automatic position reporting to the ground-based ATC system to supplement,or be in lieu of, radar.
- As a sensor to drive suitable cockpit displays to provide pilots with 4-D guidance for precision approaches and landings and with the capability of assuring air-to-air self separation.
- For automatic flight control system coupling

In addition, when applying differential GPS to precision approach and landing operations, the following unique GPS characteristics could be used to substantial advantage:

- Omni-directional (360°) azimuth coverage with linear measurement of track displacement.

- From 1.5° (or less) to 45° (or more) elevation coverage on a 360° (omni-directional) basis.

- Continuous measurement of distance and time to TDZ on approaches permitting ±5 second accuracy for landing at desired arrival time at TDZ (auto throttle coupling optional).

- Continuous measurement of distance and time to key altitude control points in the differential GPS service area during departure, e.g. per SID's.

For fixed wing aircraft, differential GPS would find wide application in extending all-weather operation to the several thousand existing airports without precision approach and landing facilities. At remote and relatively unimproved locations, it would be useful not only as an approach and landing aid but also as a means of achieving the high accuracy needed to improve aerial exploration and mapping; e.g., it could support aerial photomapping without the need to establish ground control, it would supply the accuracy needed to permit hydrographic surveys to be conducted by aircraft and it would improve crop dusting operations.

For helicopters differential GPS precision approach and landing capability could be used to serve a variety of locations:

- Dedicated helipads at conventional fixed wing airports.

- Heliports in city centers and urban areas, considering that they may be located on the surface, on elevated structures specially constructed for this purpose (e.g., over warehouses, wharves, railroad yards, etc.), or on tops of buildings.

- Helipads located on oil production platforms offshore.

- Heliports in remote areas (e.g., Alaska) or mountainous regions (e.g. Appalachia).

- Heliports required for corporate/business purposes (e.g., next to manufacturing facilities).

Thus, the potential uses of differential GPS by the civil aviation community are many, varied and of extreme value.

3.2 HELICOPTER REQUIREMENTS FOR DIFFERENTIAL GPS

Helicopter operations requiring differential GPS capabilities are those in which landings must or should be made in IMC conditions equivalent to Category I, II and III conditions. Typical of these operations would be emergencies of all types, routine police operations and scheduled commuter and cargo service.

For helicopters, conditions requiring differential GPS accuracies will occur more frequently than for fixed wing aircraft. For example, although a 200 ft. ceiling requiring Category I accuracy may exist as measured from the surface, a landing on a 100 ft. elevated heliport would require landing navigation accuracy equivalent to a Category II ILS/MLS, and on a 200 ft. elevated heliport, accuracy equivalent to a Category III (zero-zero) ILS/MLS.

Another helicopter requirement for differential GPS is implicit in the operation of helicopters into and out of conventional (CTOL) airports where discrete, narrow width routings must be followed to and from a dedicated helicopter landing/takeoff

area on the CTOL airport. Such operations should be possible independent of and simultaneous with fixed wing approaches and departures in weather conditions at least equal to those under which airline operations are conducted at that particular airport. 360° Azimuth coverage is required for helicopter operations along with variable glide slopes.

Thus, a differential GPS capability through Category III is needed for several types of helicopter operations which utilize the widespread, diverse helipads/heliports listed in Section 3.1. A mitigating factor in the case of helicopters is that their ability to be flown at low speed greatly enhances the pilot's visual acuity and thus "softens" to some extent the approach/landing navigation accuracy otherwise required by high performance airplanes under comparable ceiling/visibility circumstances. The relationship between horizontal and lateral velocity in an instrument approach vs. navigation accuracy appears to be a subject for further useful study.

3.3 POTENTIAL SUPPORTERS

Potential civil supporters of differential GPS would include the following diverse users and organizations:

- Helicopter Association of America
- Commercial Air Lines/Commuter Service
- Airline Pilots Association
- Air Cargo Companies
- FAA
- Aircraft Manufacturers
- GPS Equipment Manufacturers
- Oil Companies

With respect to the civil air community's support of a differential GPS development program, the first point to be recognized is that the industry by and large is not really aware of what differential GPS is, what its advantages are, why it may be needed, and what it will cost. Accordingly, a study of differential GPS by NASA's Ames Research Center is considered to be very timely.

Once a successful differential GPS T&E Program is underway, the civil aviation community can be brought into an informed position with respect to differential GPS. Industry might then fund further differential development, including especially helicopter manufacturers and operators, GPS equipment manufacturers, and petroleum production companies. A convincing case would have to be made, however, that risks in further R&D are minimal and that the ultimate product will be cost effective.

The civil helicopter community is the leading civil air supporter of GPS at this time. This has been evidenced on numerous occasions by the helicopter industry's representative organization, the Helicopter Association of America, in testimony before the Congress and in other statements and presentations. Most recently, during the HAA/NASA Advanced Rotocraft Technology Workshop held on December 3-5, 1980, the consensus of a panel of twelve outstanding helicopter user speakers was that GPS is urgently needed at the earliest possible date to improve helicopter all-weather operational capability. The full text of these speakers' presentations, including their endorsements of GPS, is reproduced in the Workshop's final report.

A likely differential GPS support effort by the helicopter industry, once the NASA T&E phase has been successfully completed, would be significant commitments to purchase both airborne and ground differential GPS equipment (this would facilitate production funding by GPS manufacturers). Ground facilities could be expected to be purchased by helicopter operators for their privately used heliports (e.g., on oil

platforms, in remote areas, and for corporate/business helipads). For publicly owned and public use heliports (even through privately owned), the FAA would probably purchase the ground differential GPS equipment. All airborne equipment would be purchased by operators, perhaps subsidized by helicopter manufacturers if they felt differential GPS would help market their product. The oil production companies could also be supporters once they are shown that differential GPS would provide greater all weather operational reliability for their helicopter support contractors.

SECTION 4

DIFFERENTIAL GPS CONCEPTS AND COST IMPACT

4.1 MAJOR IMPLEMENTATION ALTERNATIVES

4.1.1 GROUNDBASED MONITORING EQUIPMENT

At least three basic types of ground-based monitoring are possible:

1. Data Link Type
2. Pseudolite Type
3. Translator Type

The data link type utilizes a benchmarked GPS set which receives GPS signals, computes its position, and compares its computed position with its known position to determine error corrections. These error corrections are data linked to GPS equipped aircraft in the vicinity and are used to correct the onboard navigation solution. Variations within this conventional type include, as discussed in subsequent sections, use of single or multi-channel sets, use of an external computer for correction computation, type of correction, number of satellites tracked, and frequency of output. The primary advantage of the data link type relative to the other basic types is that it requires little change to airborne or ground GPS sets. Other advantages are that no new frequency allocation will be required and the technique is suitable for post processing applications. Its primary disadvantage is that it requires a separate data link; this disadvantage disappears if a data link is otherwise available. Figure 4-1 illustrates this type.

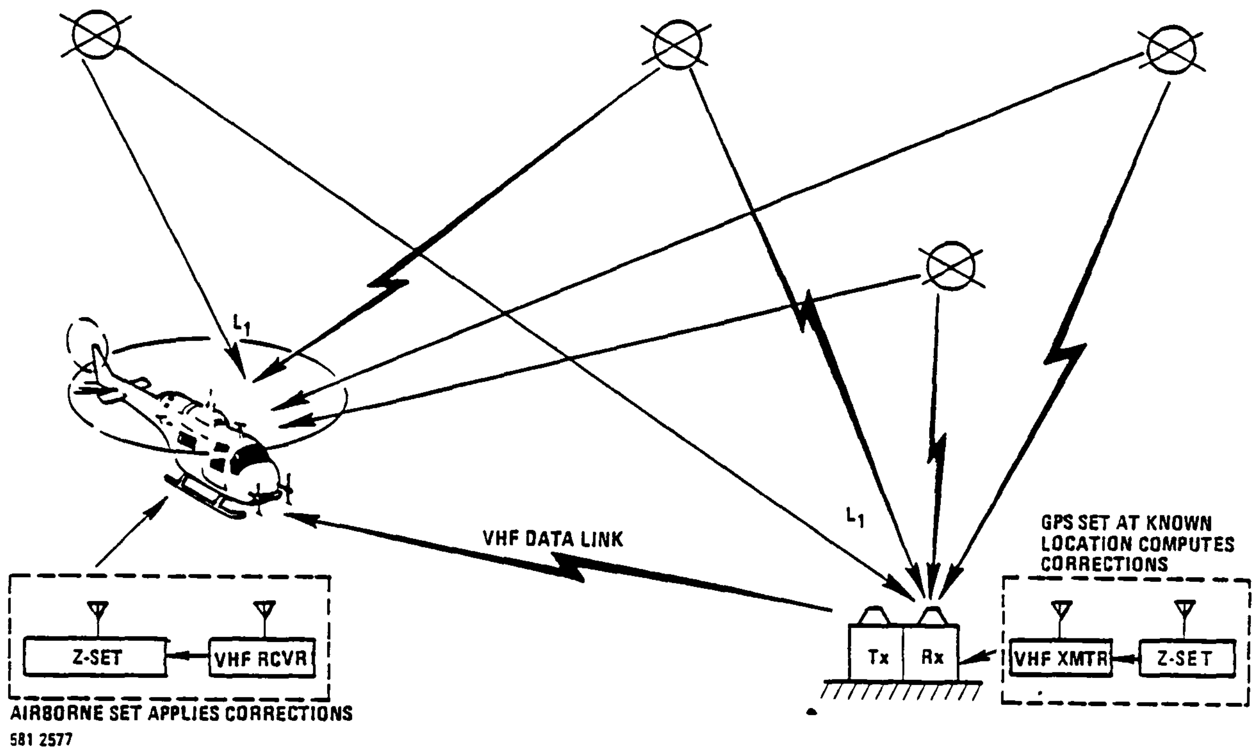

Figure 4-1. Differential GPS - Data Link Type

The pseudolite type monitors GPS signals and computes corrections in the same manner as the data link type, but it also generates its own PN code and navigation message which is transmitted at the GPS L_2 frequency along with correction data for the GPS satellites. The PN code and navigation message generated at the calibration site provides another GPS signal source from, in essence, a ground-based or pseudo satellite, hence the term pseudolite. The pseudolite type includes variations similar to those possible with the data link type. The pseudolite has several advantages: (1) the airborne GPS set can function as the differential data receiver avoiding the necessity for a separate differential data airborne receiver; (2) the pseudolite's navigation signal provides a highly accurate single line of position (LOP) which should reduce UERE errors and/or DOP in its vicinity; (3) the PN transmission provides inherent protection for the correction data; and (4) a side benefit is provided in test programs conducted with the current six satellite GPS constellation

because the additional pseudolite signal source permits operation with less than four satellites in view, thus extending available test time. Pseudolites were the basis for inverted range testing during the advanced development phase of the Phase I GPS test program at Yuma, Arizona. Disadvantages of the pseudolite type are: (1) extra cost for the ground equipment for such items as wave form generators, time synchronization equipment and L-band transmitters; (2) added complexity relative to the data link type; (3) possible near/far problems in aircraft reception of the different strength pseudolite and satellite signals depending on pseudolite location; (4) the need for two antennas on the aircraft to ensure full time reception; (5) the possible need for a new frequency allocation; and (6) possible problems for non-participating users in the vicinity of the L_2 ground transmission. Figure 4-2 illustrates this type. Figure 4-3 illustrates a Z-Set mechanization of the pseudolite approach.

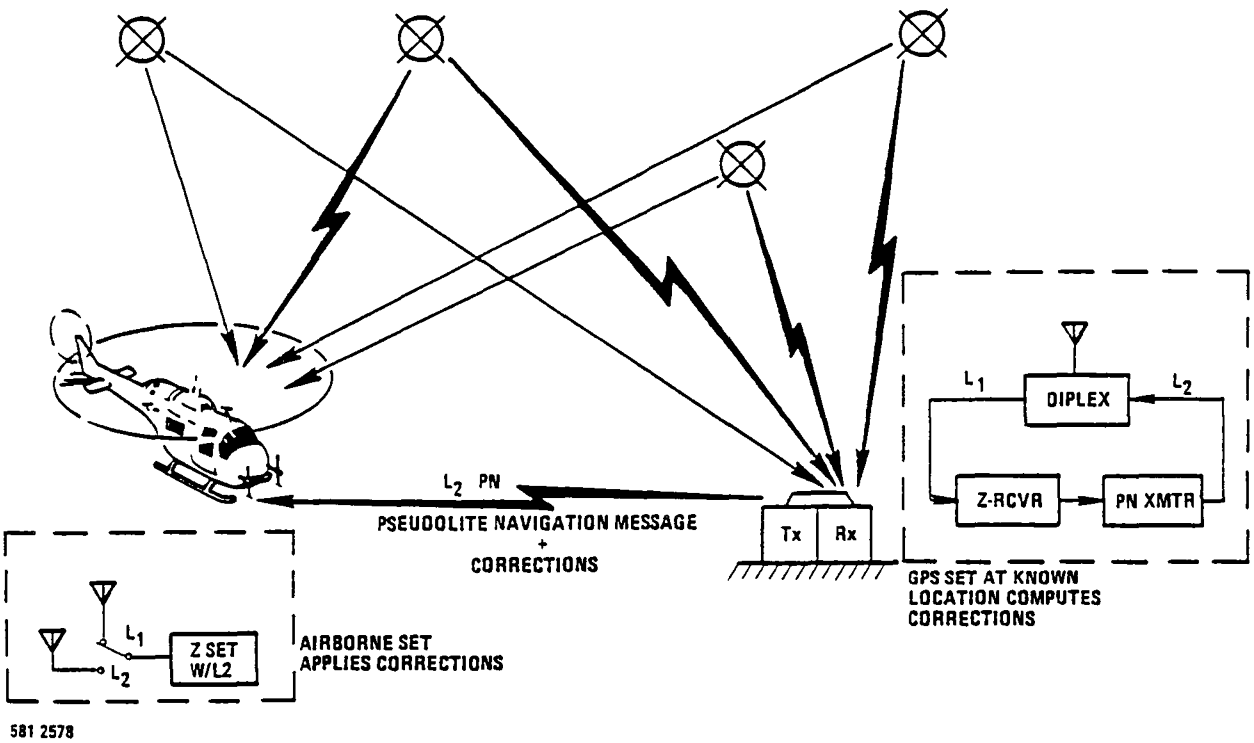

Figure 4-2. Differential GPS - Pseudolite Type

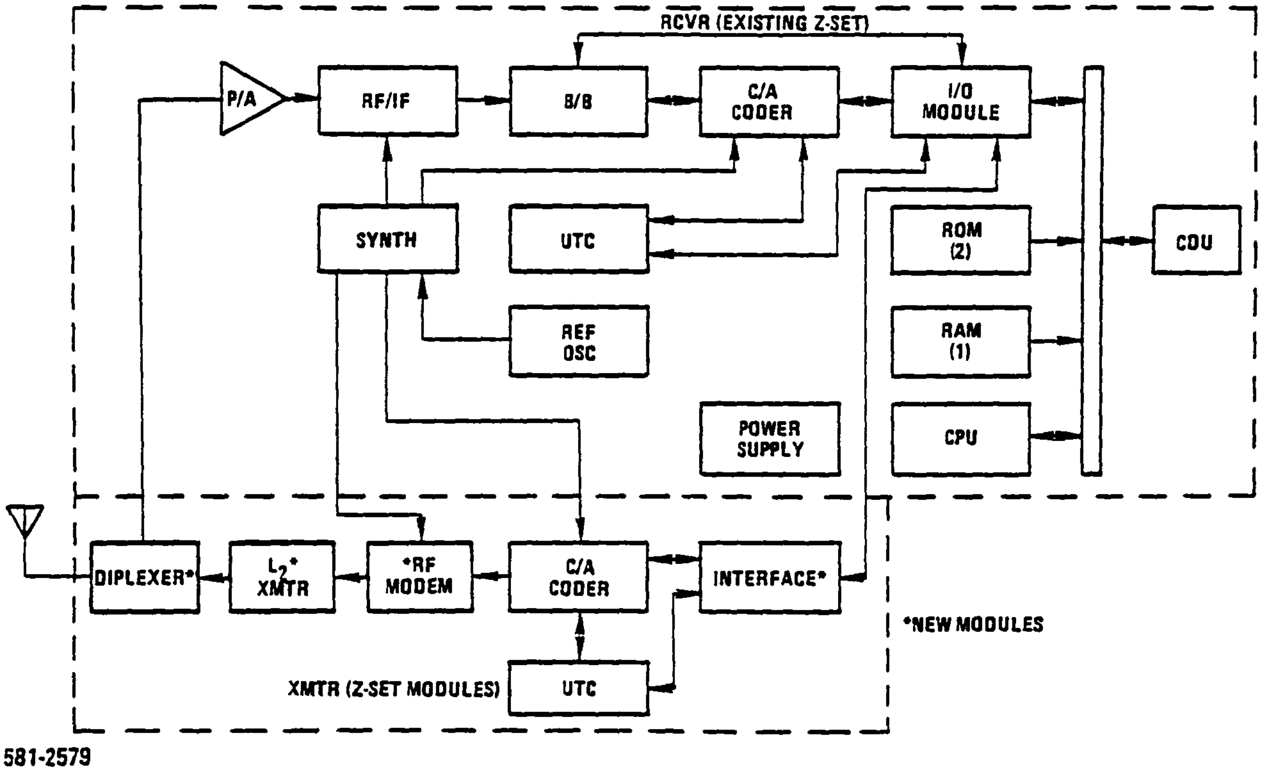

Figure 4-3. Pseudolite Modules

The translator type merely offsets the frequency of GPS signals received by its benchmarked antenna and retransmits them to airborne users on another L-band frequency, L_n. The signals from all available satellites are retransmitted continuously, and the airborne GPS set computes the corrections for its constellation knowing the location of the transponder. No GPS set is required at the ground site and no processing is accomplished or correction data generated at the ground site. Primary advantages of the translator type are minimal complexity and low cost for the ground installation to the point where it becomes practical when one or a few helicopters must serve many landing sites, such as oil rigs. Low power, portable ground stations can also be envisioned. Disadvantages of this type are: (1) two GPS antennas are required on the aircraft; (2) an L-band translator is required on

the aircraft to reverse the translation accomplished on the ground; (3) a multichannel GPS receiver may be required on the aircraft; (4) a new frequency allocation would be required; (5) near-far problems will be encountered in aircraft GPS signal reception; (6) user dynamics may be restricted; and (7) the pilot will be required to enter the coordinates of the ground translator into the airborne system. Figure 4-4 illustrates this type.

4.1.2 COMPUTATION AND APPLICATION OF CORRECTIONS

The correction data which would typically be required in the differential mode would include the following:

- Correction data for 3 to 8 satellites
- Correction data quality estimates

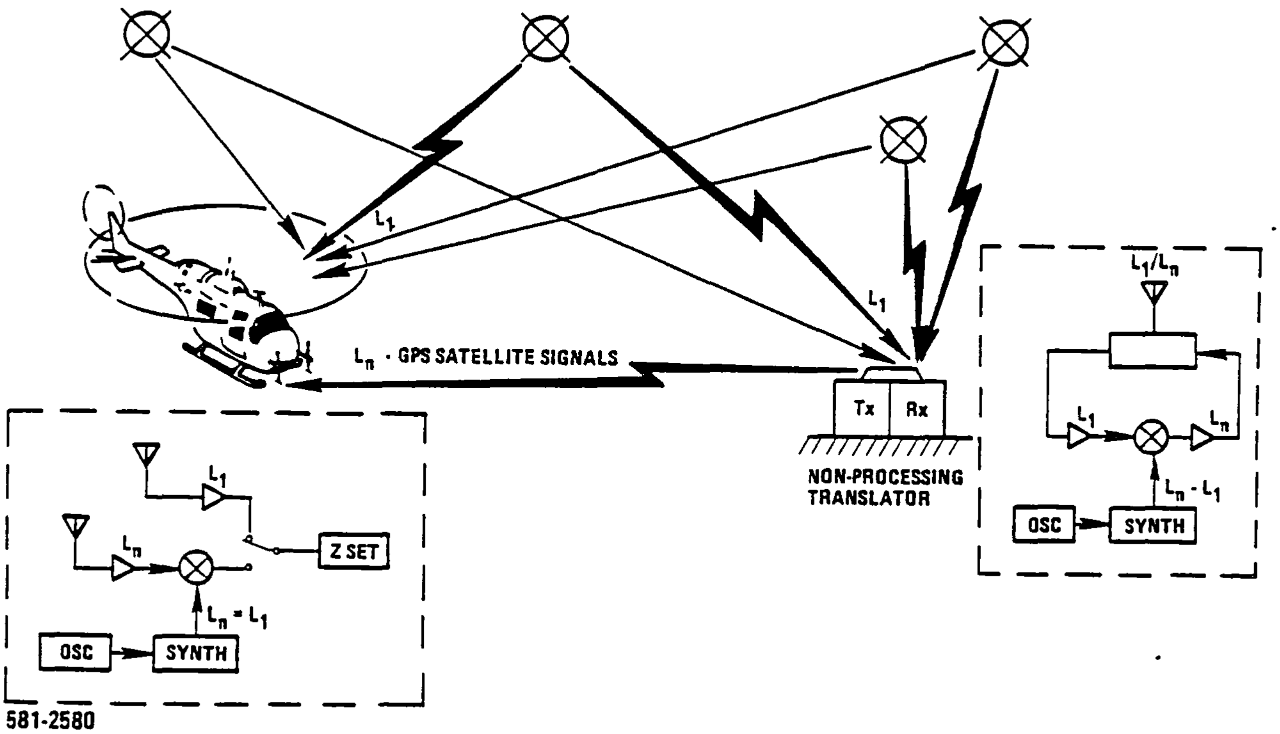

Figure 4-4. Differential GPS – Translator Type

- Satellite data and I.D.
- Ground/User coordination data
- Ground equipment status
- Correction data encoding (1), (2)
- Correction data quality estimates (1), (2)

For the data link and pseudolite concepts, two basic types of corrections could be computed and transmitted by the calibration site: (1) X, Y, Z position corrections, or (2) UERE corrections for each satellite. In both cases, the corrections would be based on comparing the GPS solution with the known location of the calibration site's GPS antenna, the difference being the correction to be applied.

The advantage of the X, Y, Z correction is that it can be applied as a simple addition to the airborne set's solution either internal to the GPS set or by an external computer. The disadvantages of the X, Y, Z correction technique are that it requires both sets to track the same satellites and that the resulting airborne solution may be less accurate than a UERE correction introduced into the airborne set's navigation filter.

The advantage of UERE correction is that it can be transmitted for all GPS satellites in view to eliminate the need for the airborne set to track the same satellites as the calibration site. The disadvantages are that (1) more data must be transmitted and (2) update rates may require the use of multi-channel sets at the calibration site. The update rate is a significant parameter for both X, Y, Z and UERE correction methods and requires further study.

For the transponder concept, no processing is accomplished at the calibration site and the GPS satellite signals are transponded continuously. The corrections are

computed by the airborne system and can be either X, Y, Z or UERE corrections determined internal to the GPS set or by an external computer. Again, X, Y, Z corrections would be simple additions to the aircraft's GPS solution while UERE corrections could be filtered along with received signals.

4.1.3 DATA LINK EQUIPMENT AND INTERFACES

The different types of data link equipment and interfaces are indicated on Figures 4-1 through 4-4. As shown in Figure 4-1, the data link concept utilizes a VHF differential data transmitter at the calibration site and a VHF differential data receiver on the aircraft. The transmitter and receiver would be interfaced to the GPS sets or, if used, separate computers via a data modem which could be a stand-alone modem or internal to the VHF equipment, the GPS sets or the separate computers. The data stream would contain some minimal error encoding. If an existing data link is available, such as planned for DABS, it could be interfaced directly.

Figure 4-3 shows the data link equipment for the pseudolite type. As indicated, the ground equipment consists of an applique to the ground GPS set interfaced directly to an L-band transmitter. The airborne GPS set receives the correction data transmission directly. Again, some minimal error encoding would be applied to the correction data transmitted.

Figure 4-4 shows the data link equipment for the translator type. As indicated, the ground equipment consists of an up or down converter interfaced directly to an L-band transmitter. A similar translator in the airborne system reconverts the translated GPS signal for direct reception by the airborne GPS set. No error encoding is introduced in this approach since no data is generated.

4.1.4 AIRBORNE GPS EQUIPMENT

4.1.4.1 Data Link Type

Figure 4-1 shows that an essentially standard single channel GPS set could be used on the aircraft in the data link approach. While standard sets could be used, a C/A Code set optimized for the differential mode would produce higher accuracies and may entail both hardware and software changes (see Section 2.2.4).

The following minor modifications would be required if standard or optimized sets were to be able to function in the differential mode:

1. If corrections were applied internal to the GPS set,
    a. A differential mode command would be required.
    b. Correction algorithms would be required.
    c. Differential mode satellite selection algorithms would be required if X, Y, Z corrections are applied.
    d. A data interface would be required.
2. If corrections were applied by the aircraft central computer external to the GPS set, only a differential mode satellite selection algorithm combined with a differential mode command would have to be added and then, only if X, Y, Z corrections are used rather than UERE corrections.

All of the modifications could be accomplished in software except for the hardware interfaces to the data link or central computer if they are not already provided as part of the airborne system.

4.1.4.2 Pseudolite Type

Figure 4-2 indicates that the airborne GPS set in the pseudolite concept would require several modifications to a standard or optimized set. These would include the following:

1. The addition of an L_2 RF front end would be required along with an L_1/L_2 switching capability.
2. The dynamic range of the RF front and would have to be increased.
3. All of the data link concept modifications would be required except for the data interface.
4. An additional antenna would be required.

4.1.4.3 Translator Type

Figure 4-4 shows that the airborne GPS set in the translator concept would require several additions/modifications to a standard optimized set.

1. An L_n/L_1 translator would be required.
2. Additional channel capacity might be needed or antenna switching capability would be required.
3. An additional antenna would be required.
4. All of the data link modifications would be required except for the data interface.
5. The dynamic range of the RF front end would have to be increased.

4.2 BASIC DIFFERENTIAL SYSTEMS COMPARISON

A review of the advantages and disadvantages presented in Section 4.1 for the three basic differential GPS concepts leads to several conclusions:

1. The data link concept requires the least amount of change to standard GPS sets for ground and airborne use in the differential mode. This is accomplished at the expense of a separate data link which may be available anyway as a low cost subsystem in support of next generation ATC operations. The data link concept could be developed and demonstrated at the least cost and with the least risk.

2. The pseudolite concept may, depending on the location of the pseudolite, provide the best accuracy because of improved geometry (i.e., lower PDOP) and would be of benefit during limited satellite availability. Also, this concept eliminates the need for a separate airborne data link receiver. However, these benefits are achieved at the expense of added complexity, risk, and cost for both ground and airborne GPS equipment. Also, these benefits may be of questionable value during the operational GPS era since (a) the accuracy improvement will not be substantial, (b) satellite availability will not be limited, and (c) a separate, low cost data link to support next generation ATC operations may be available at no cost to the data link concept.

3. The translator concept would provide the lowest cost ground installation at the expense of considerable complexity in the airborne GPS system and at some technical risk. This concept could be cost effective where a few helicopters serve a large number of sites. Operations of this type are, however, not common, and the small amortization base will make development of a cost effective translator system difficult.

4.3 DIFFERENTIAL GPS COST IMPACT

The extra cost of differential GPS relative to the conventional mode is (1) that attributable to necessary changes and additions to the airborne conventional set and (2) that incurred in the acquisition, installation, and operation of the calibration site equipment. The impact of these extra costs will be a function of the eventual cost of a conventional civil set, the availability of suitable data link receivers in participating aircraft, number of users served by a calibration site, and type of differential concept employed. Uncertainties in the outcome of the final product design make the eventual cost of GPS navigation receivers for general aviation difficult to predict. Some insight is provided by a January 1979 report titled, "Avionics Cost Development for Civil Application of GPS" by ARINC for the FAA. The report concludes that a civil set comparable to the GPS Phase I Z-Set could be produced in quantity for under $5,000 (1977 dollars).[8,9]

A preliminary assessment of the cost impact of differential GPS based on expected trends in the 1985–1990 time frame is summarized in Tables 4-1 and 4-2. The impact is expressed as a percentage of the cost of a conventional GPS set and is based on (1) assumed complexity of the differential equipment relative to a conventional set, (2) 50 or more users per site, (3) assumed high quantity production, (4) negligible calibration site operating costs, and (5) negligible amortized development costs.

4.3.1 CALIBRATION SITE COSTS

As Table 4-1 shows, the installed cost of calibration site equipment for the data link and pseudolite concepts is estimated to be about 200% of the cost of a conventional set and for the translator concept as about 20% of the cost of a conventional set. Amortized over 50 users, this calibration site cost per user would

Table 4-1. Differential GPS Calibration Site Acquisition and Installation Cost

Technique	Required	Cost[1]	Cost[2]
Data Link	• Standard GPS Set • VHF Transmitter with Data Modem, Antenna • Interfaces/Chassis	~ 200%	~ 4%/user
Pseudolite	• Standard GPS Set • PN/L_2 Applique	~ 200%	~ 4%/user
Translator	Translator ($L1/L_n$)	~ 20%	< 1%/user

[1]Expressed as a percentage of the cost of a standard GPS set.

[2]50 users assumed.

Table 4-2. Differential GPS Airborne User Cost Impact

Differential Technique	Differential Equipment Required	Cost Impact[1]
Data Link, Suitable VHF Data Link Receiver Available on Aircraft	Minor GPS set Mods	~ 0%
Data Link, Suitable VHF Data Link Receiver Not Available on Aircraft	VHF Data Link Receiver VHF Antenna Minor GPS set Mods	~ 20%
Pseudolite	RF Mods Extra Channel Extra Antenna	~ 30%
Translator	Translator (L_n/L_1) Extra Channel Extra Antenna	~ 50%

[1]Expressed as a percentage of the cost of a standard GPS set.

be about 4% for the data link and pseudolite concepts and less than 1% for the translator concept. Thus, ground equipment for differential GPS is not considered a major cost factor if a reasonable number of users are served per site.

4.3.2 USER EQUIPMENT COSTS

In the data link concept, as Table 4-2 shows, the extra cost impact of the airborne differential capability is estimated as about 20% of the cost of a conventional C/A Code set if a dedicated differential data link receiver must be supplied. Where suitable data link receivers are available on participating aircraft, the cost impact would be negligible.

In the pseudolite concept, as indicated in Table 4-2, the extra cost impact of the airborne differential capability is estimated as the equivalent of 30% of the cost of a conventional set.

For the translator concept, Table 4-2 shows that the extra cost of the airborne differential capability is estimated as 50% of the cost of a conventional set. Because of its high airborne cost and low ground cost, this concept would be of interest primarily where one or a few helicopters serve many sites, such as oil rigs.

For purposes of comparison, the extra cost of a single channel, P-Code implementation is estimated as 20% of the cost of a single channel C/A Code set. This factor could vary substantially depending on mechanization techniques and production quantities.

4.3.3 CONCLUSIONS

The data link differential technique appears likely to be the most economical, least complex of the three differential concepts considered. Also, development cost and

risk will be less for this concept than for the other differential approaches. It is, therefore, the concept used as the model for planning the T&E program in a later section of this report. Since the other differential techniques offer benefits for special applications, they should be studied in greater detail in the initial phase of the T&E program.

SECTION 5

THE CASE FOR DIFFERENTIAL GPS

5.1 PRECEDENT

The precedent for enhancing navigation system accuracy through use of differential techniques is well established. Omega is utilized in the differential mode to achieve an order of magnitude improvement in Omega navigation accuracy near shore, and it is used in the relative mode to achieve similar improvements for at sea rendezvous. Differential Loran-C, in the form of calibrated chain operations, is utilized for hydrographic surveys and confined waterway navigation. Differential TRANSIT satellite positioning, in the form of translocation, is used to extend conventional (i.e., non-differential) accuracies of several meters to the 10 to 20 cm range for geodetic survey applications.

5.2 POTENTIAL FOR IMPROVING DEGRADED C/A CODE PERFORMANCE

Differential GPS has the potential to mitigate intentionally degraded C/A Code conditions so that basic GPS performance is retrieved in local areas; relative GPS performance holds similar promise for enroute operations. Accordingly, if differential/relative navigation techniques are technically compatible with the type of intentional degradation to be encountered, civil users should be able to utilize GPS effectively even under intentionally degraded C/A Code conditions. In this case, inherent relative GPS accuracy with altimeter aiding would permit degraded C/A Code signals to be used for all RNAV/IFR enroute and terminal area operations;

differential GPS would extend that capability to at least non-precision IFR approaches and landings in local areas. This would bring the considerable benefits of GPS to the civil air community at the earliest possible time.

5.3 POTENTIAL FOR IMPROVING UNRESTRICTED GPS PERFORMANCE

When the civil community receives unrestricted access to GPS signals, differential GPS will extend conventional GPS performance capability to at least Category I approach and landing conditions and may extend it to Category II and III at many sites, particularly for helicopters. The need for these capabilities is implicit in the FAA IFR standards; i.e., if aircraft are to fly in all-weather conditions, the need for differential GPS-type accuracies exists.

Currently, the need for Category III type accuracies is not being satisfied because Category III navigation aids are not available. In Category III situations, flights are rerouted to alternate sites with higher minimums or cancelled. In the majority of Category II situations, flights are also rerouted to alternate sites with higher minimums or cancelled due to the limited number of Category II facilities and qualified pilots. Category I needs fare somewhat better, but, even here, they are satisfied at only a small percentage of our airports and rerouting or cancellation is the norm under these conditions rather than the exception.

Thus, differential GPS has the potential to substantially improve the availability of precision approach and landing facilities worldwide.

5.4 DIFFERENTIAL GPS VALUE

Differential GPS has the potential to extend a relatively low cost all-weather capability to thousands of public service and private airfields which would not be

likely to obtain it otherwise. The availability of widespread all-weather capability would be extremely valuable to commercially-based and private flight operations:

1. It is essential if helicopters are to realize their full potential for emergency, commuter and cargo service;

2. It offers the potential for significant savings from reduced fuel use for alternate site routing and missed approaches and from lowered fuel reserve requirements for alternate site planning;

3. It will substantially improve safety by reducing missed approaches and assisting in aborted takeoffs;

4. It is invaluable for those situations when the weather closes-in at alternate sites and when emergencies exist at sites with Category I, II or III conditions;

5. It will increase productivity and result in more cost-effective, safer flight operations in general.

The use of differential GPS for all-weather applications could begin when the civil community obtained access to the undegraded C/A Code provided that optimized C/A Code sets are available with differential performance capability approaching that predicted for the differential P-Code. In the meantime, differential GPS appears to have the potential in local areas to derive basic C/A Code performance from the degraded C/A Code. This would support at least non-precision operations and approach Category I capability. Thus, differential GPS, together with inherent similar relative accuracy for enroute and terminal area operations, shows promise of permitting the civil community to use GPS effectively as soon as it becomes operational. The civil community would thereby derive many of the considerable benefits of GPS in the areas of improved safety, productivity and economy at the earliest possible time.

In another vein, use of differential GPS for such high precision operations as airborne hydrographic surveys, side looking radar (SLR) surveys, and aerial photography will provide substantial savings over current operations. For SLR mapping and aerial photography, differential GPS will eliminate the costly establishment of accurate ground control and, for hydrographic surveys, permit faster, more economical airborne surveys rather than shipborne surveys. These high precision operations will generally use post processing rather than real time methods, but the basic differential techniques will be the same.

5.5 CONCLUSIONS

As indicated in Section 4.3, differential GPS is expected to be an affordable option for conventional GPS users. Its affordability coupled with its potential to mitigate early C/A Code signal degradation, its subsequent value in providing all-weather capability, and its value for special, worldwide high precision applications make its widespread use likely and warrant its early development.

SECTION 6

RECOMMENDED DIFFERENTIAL GPS TEST PROGRAM

Figure 6-1 shows a time phased sequence of tasks designed to investigate differential GPS concepts, performance, procedures, and general utility for helicopters. Also shown are time phased costs for contractor effort in the recommended test program. Effort in each task should include the following:

Task I - Differential GPS T&E System Definition

Task I analyzes differential GPS techniques and defines a differential GPS T&E System based on use of the Z-Set and NASA provided airborne equipment and range instrumentation. Z-Set modifications needed for the selected T&E System are identified as well as facilities and equipment to be supplied by NASA. A differential GPS Techniques Report, a preliminary design and system specification for the selected T&E System and required Z-Set modifications, and a budgetary cost and schedule estimate to build and install the selected T&E System are the principal outputs of the Task I.

Task II - Pilot-in-the-loop Simulations

Task II develops differential GPS software modifications for NASA, Ames GPS simulation program and supports differential GPS simulation effort at NASA, Ames. Software modifications consist of a differential corrections generator for NASA's GPS signal generator program and a software modification for the PDP-11 in the cockpit simulator to apply the corrections. On-site simulation support is provided to assist NASA in simulation planning, simulations, and data reduction. A final report

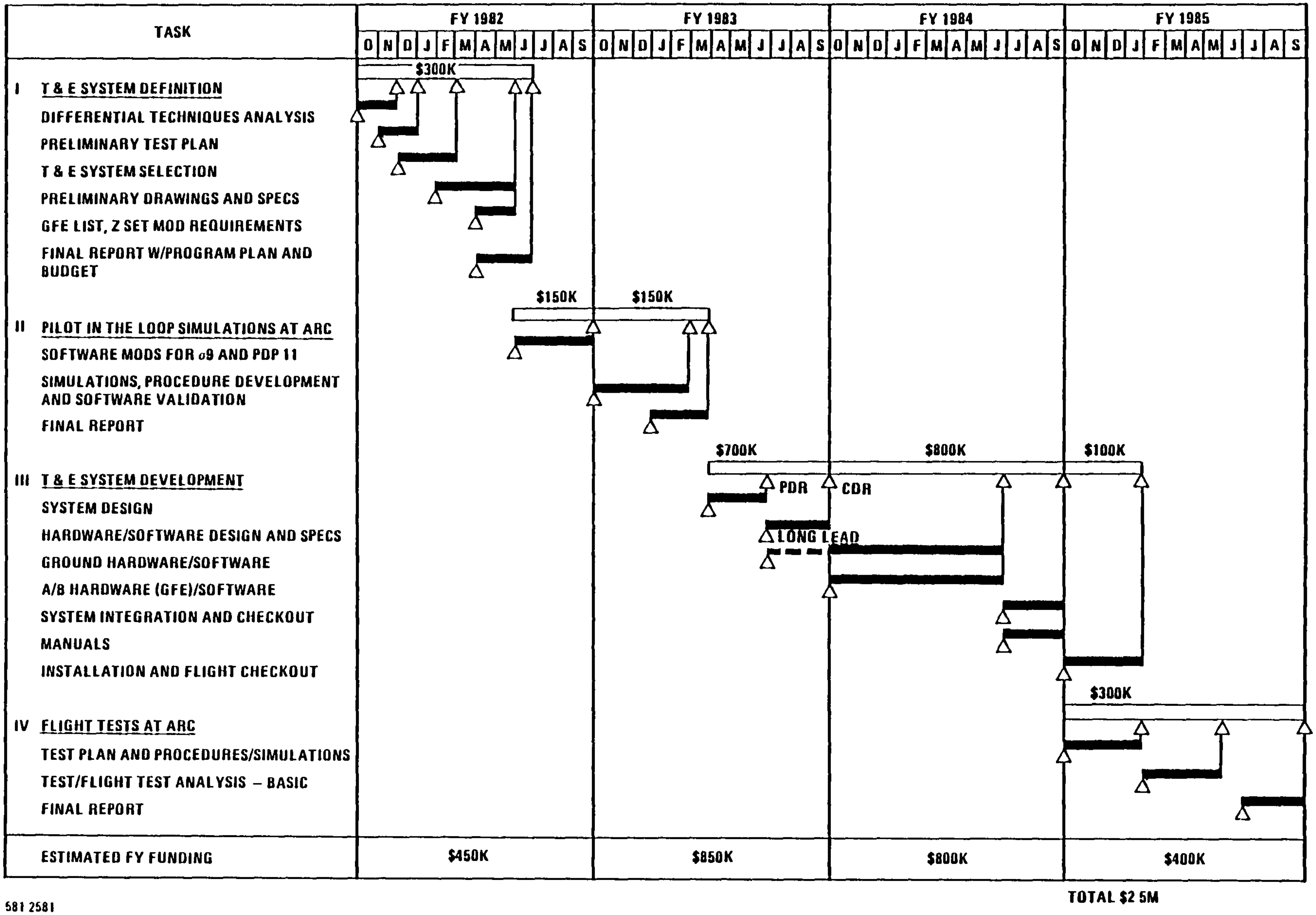

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Figure 6-1. Differential GPS T&E Program Plan

including simulation results and recommendations for the flight test program are the principal output of Task II.

Task III T&E System Development

Task III provides an operating T&E System at NASA, Ames per Task I specifications. All airborne equipment including installation and checkout is assumed GFE.

Task III consists of the following:

1. T&E System hardware design and documentation including drawings, specifications, manuals, and GFE list.
2. T&E System software development and checkout including all calibration site software, required airborne software modifications for interfaces and application of corrections, recording and data reduction software, and software documentation.
3. Calibration Site Terminal fabrication, integration, and checkout including one modified Z-Set, a minicomputer and peripherals, a transmitter and antenna, interconnects, and chassis.
4. On-Site assistance to NASA in the installation and flight checkout of the T&E System at NASA, Ames.

Task IV - Flight Tests

Task IV provides on-site support to NASA during the flight test program at ARC. Support includes test planning, test monitoring, equipment and software maintenance, data reduction, and post flight analysis. A final report including the results of the test program and recommendations for development of differential GPS equipment, procedures, and navigation accuracy standards will be the principal output of this task.

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this study effort, the following conclusions are drawn leading to the recommendation that a T&E program be initiated as soon as possible for differential GPS:

1. Civil users may encounter intentionally degraded C/A Code signals for a few to several years after GPS becomes operational in 1987 but can expect to receive unrestricted access to C/A Code signals thereafter, followed eventually be unrestricted access to P-Code signals;

2. Inherent relative GPS accuracy coupled with altimeter inputs has the potential to permit civil users to utilize the intentionally degraded C/A Code for all RNAV/IFR enroute and terminal area operations; differential GPS has the potential to extend use of the intentionally degraded C/A Code signals to at least non-precision approaches and landings in local areas. Thus, the performance improvement potential of differential GPS coupled with similar improvement inherent in the relative GPS mode may permit civil users to utilize GPS effectively even under intentionally degraded C/A Code signal conditions;

3. Conventional use of unperturbed C/A Code signals will accommodate all RNAV/IFR enroute, terminal area and non-precision approach and landing requirements on a full time basis but will not accommodate RNAV/IFR Category I precision approach and landing conditions under current FAA regulations.

4. Conventional use of the P-Code will not materially enhance civil enroute or non-precision approach and landing operations relative to conventional use of the C/A Code; nor will it provide precision approach and landing capabilities. Thus, widespread early conventional use of the higher cost P-Code sets by the general aviation community does not seem likely or warranted, particularly since P-Code availability could lag C/A code availability considerably.

5. Differential techniques are expected to extend P-Code performance to Category I operations on a full-time basis and possibly to Category II and III, particularly for helicopters. C/A Code receivers will have to be optimized for the differential mode to achieve similar performance. FAA navigation standards should be carefully reviewed relative to differential GPS characteristics to ensure that maximum use for precision approach and landing operations is achieved.

6. The civil air community will benefit substantially if differential techniques can recover basic GPS performance locally and relative GPS performance with altimeter aiding can recover it enroute and in terminal areas. Civil users would, then, have access much sooner than otherwise likely to such GPS benefits as improved safety, increased productivity, expanded access to congested and remote facilites, enhanced emergency operations, and improved ATC operations. These benefits will continue to accrue to the civil air community after degraded signal conditions end because differential GPS has the potential to extend basic GPS performance to Category I operations and, perhaps, to Category II and III conditions to provide a truly all-weather capability to suitably equipped aircraft. The helicopter community, in particular, will benefit from being

able to operate in the reduced minimums at a virtually unlimited number of landing sites since temporary, elevated, isolated, and congested heliports will be readily accessible continuously to maximize productivity.

7. Differential GPS should prove to be an affordable option for conventional GPS users.

8. The potential benefits of differential GPS, particularly for helicopters, warrants a helicopter-based T&E effort to corroborate high accuracy differential GPS performance, assess differential GPS suitability for precision approaches and landings, develop differential GPS procedures, define differential GPS equipment requirements, and confirm differential GPS affordability. Preliminary cost and schedule assessments indicate that the T&E effort can be completed by 1985 at an estimated cost of approximately $2.5 million. Completion of the T&E program by 1985 would permit subsequent development of a commercially available differential GPS capability by the time the operational GPS space segment is deployed.

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APPENDIX A

GPS DESCRIPTION AND STATUS

APPENDIX A

GPS DESCRIPTION AND STATUS

GPS is a satellite based navigation system under development by DoD. It is designed to provide suitably equipped users with worldwide, continuous, highly accurate, 3-D navigation and time. GPS consists of three segments: the space segment, the ground control segment, and the user segment (Figure A-1).

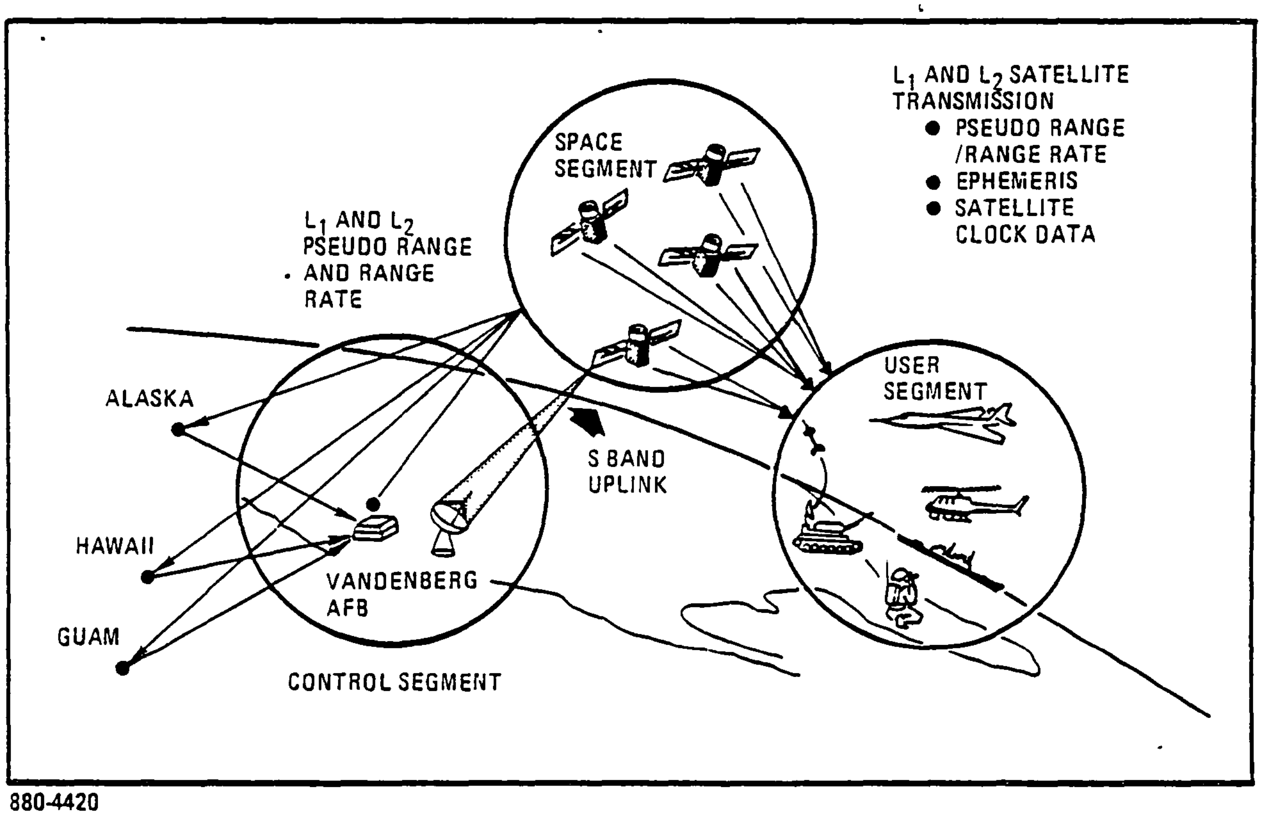

Figure A-1. NAVSTAR GPS Segments

In the operational space segment, a constellation of 18 satellites will circle the earth in nominal 10,900 nautical-mile orbits with a period of 12 sidereal hours. The constellation will be configured in several 55° included orbital planes with the objective of providing direct, line-of-sight navigation signals continuously from at least four satellites to any point on or near the surface of the earth. Each satellite transmits its navigation signals on two L-Band (UHF) frequencies.

The signals consist of a Precision (P) Code and a Coarse Acquisition (C/A) Code which are both pseudorandom digital sequences used for ranging. The signals also contain a navigation message which provides satellite position, time, and atmospheric propagation correction data generated by the ground control segment. The two-frequency transmission permits users to correct for frequency sensitive propagation delays and anomalies.

The ground control segment has four monitor stations which are located at Guam, Hawaii, Alaska, and Vandenberg AFB in California. A Master Control Station is also located at Vandenberg. The monitor sites track the satellites via their broadcast signals as they come into view. The Master Control Station collects the tracking data and generates the navigation message for each satellite which is uploaded to each satellite's memory daily via S-Band telemetry link. In this way, the satellites are able to broadcast an accurate description of their position as a function of time.

The user segment consists of ground-based, marine, airborne, and spaceborne platforms equipped with a GPS receiver/processor capable of tracking four satellite signals either simultaneously or sequentially. Part of the task will be to select which four satellites to track to optimize accuracy as the satellites slowly pass by. Position is computed by making time-of-arrival (TOA) measurements on the P or

C/A Code transmitted from discrete satellite positions defined by the navigation message. Each set of four TOA measurements permits determination of the four independent variables of latitude, longitude, elevation, and user clock offset. Velocity is computed by making doppler measurements on the carrier frequency. Each set of four doppler measurements permits determination of the four independent variables of 3-D velocity and user clock drift. Navigation is accomplished via a Kalman filter which propagates a continuous navigation solution based on the TOA and doppler measurements. Use of the filter's propagation capability permits temporary operation on fewer than four satellites.

Full 3-D Operational capability with 18 satellites is expected by the end of 1987 with 2-D operational capability commencing at the end of '85. In the meantime, a five to six satellite constellation will be maintained for test and evaluation (see Figure A-2).

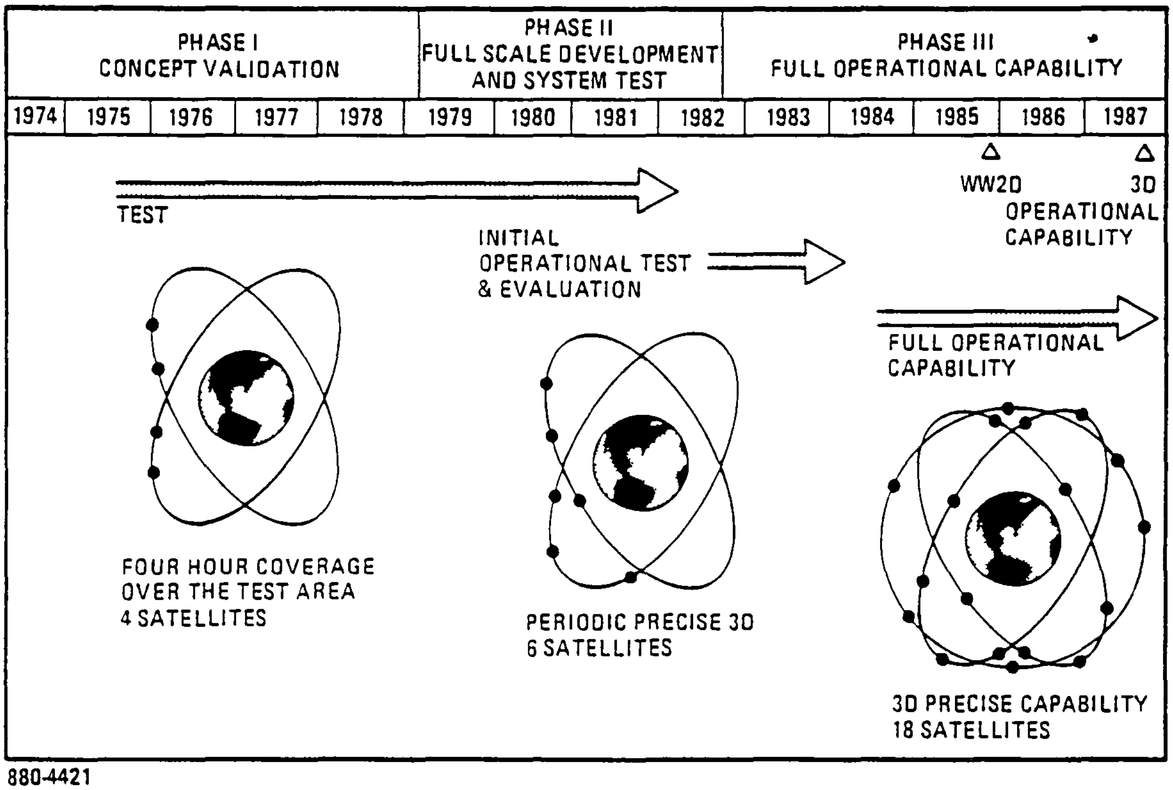

Figure A-2. Schedules and Orbital Configurations

PHASE I USER EQUIPMENT

As part of the Phase I Program, four types of user equipment were developed to demonstrate the navigation accuracy and other parameters of GPS. This development culminates eight to ten years of prior breadboarding, studies and demonstrations of 621B, TIMATION, and the Defense Navigation System Development Program. Field testing of the Yuma Test Range has been completed on four types of user equipment, designated the Set X, Set Y, Manpack and Set Z. These sets, described in Table A-1 are designed to satisfy performance requirements which may be operationally or platform unique in the future.

Table A-1. Phase I NAVSTAR User Sets

User Set	Characteristics	Platform	Frequency	Code	Channels
X	High Accuracy High Accuracy High Dynamics Fast Fix	B-1, F-4 Submarine	L_1/L_2	CA/P	4
Y	Low Dynamics	Ships	L_1/L_2	CA/P	1
MP	Small Low Power	Manpack Vehicle	L_1/L_2	CA/P	1
Z	Low Cost Low Dynamics	Civil Users	L_1	CA	1

X-SET - The Continuous Set

Applications in which the dynamics are high, the expected jamming is severe and/or a fast fix is required call for a set that can track four satellites simultaneously to provide continuous navigation with position and velocity information. The X-Set is designed to work with two antennas where shadowing is severe due to dynamics or where combined satellite and inverted range tests are desired. The set may be

"aided" by an inertial platform to provide the ultimate in performance for GPS equipment.

Y-SET - The Sequential Set

The main differences between X and Y are in the receiver (4 carrier channels versus 1 carrier channel) and Navigation processor software associated with sequencing, alerting, etc. As a result, the Y-Set contains less hardware than the X-Set and is intended for users who will experience less dynamics and less jamming than the X user. Y also takes approximately 3 times longer to obtain a first fix and requires smaller position and velocity uncertainties. While X is the ultimate in performance, Y costs less.

MANPACK - The Small Set

Manpack was designed for small size (27 lbs.), low power (27 watts) and relatively low dynamics (30 m/sec). It supports a wide variety of Army and Marine Corp missions. Manpack contains a single channel sequencing receiver, operates with both C/A and P-Codes and resolves ionospheric uncertainties through the use of L_1 and L_2 frequencies. The user is able to navigate or position himself in either the Military Grid Reference System (MGRS) or local datum coordinates. He can display distance and azimuth to selected rendezvous locations with reference to true, grid or magnetic north.

Z-SET - The Low Cost Set

The Z-Set is a low cost MIL-Spec Avionics navigator. It consists of a sequential receiver like Y, but operates only at the L_1 frequency and uses only the C/A Code. To reach a design-to-cost goal as an avionics set required numerous interacting

trade-offs of cost versus performance. Table A-2 summarizes its performance capability with respect to the X-Sets.

Table A-2. Z-Set Trades Performance for Low Cost

GPS Set Features	X	Z
Pseudorange Measurement Accuracy (3σ) Meters	6	60
Jamming Vulnerability	Low	High
Normal Time to First Fix	2-3 Min.	5-8 Min.
Capable of Inertial Aiding	Yes	No

The Z-Set shown in Figure A-3 is housed in a 3/4 ATR short. It weighs 34 pounds and requires 53 watts. The unit is put together in slices, much like the ARC-164 UHF-AM radio which was the first major design-to-cost military avionics program.

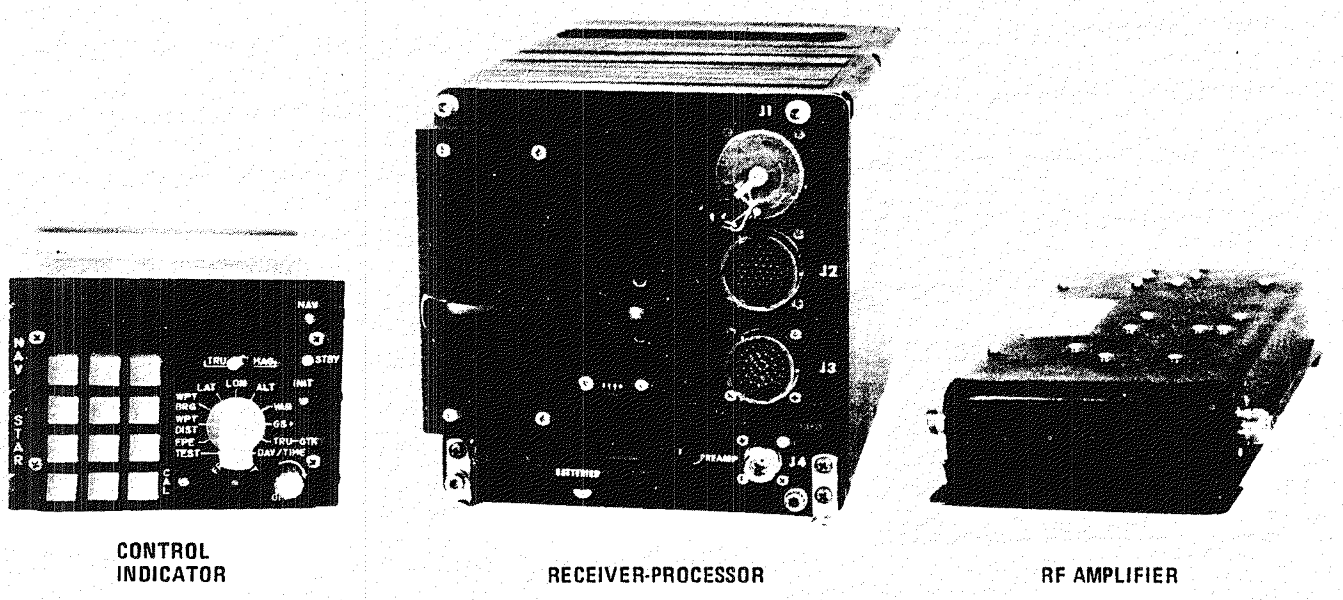

Figure A-3. Z-Set Hardware Configuration

PHASE I FIELD TEST RESULTS

Navigation Accuracy

To date, GPS developmental Test and Evaluation has included over 700 field tests on 11 host vehicles with 7 types of GPS user equipment. Conducted over a period of two years, this extensive field test program addressed more than 20 major objectives ranging from system vulnerability to user applications. Test aircraft included a Navy F-4J, an Air Force C-141, a Navy P-3B, and an Army UH-1H.

Testing was conducted primarily at the U.S. Army Yuma Proving Ground and off the Southern California coast. Yuma's Precision Automated Tracking System, a computer-based laser tracking system, provided reference vehicle position for GPS accuracy determination at Yuma. Under most conditions the laser system provided position and velocity accuracies of 1 meter and 0.1 meter/sec., respectively.

Table A-3 lists the 50th and 90th percentile values for three-dimensional system accuracies. The data represents a total of 76 missions conducted from November 1978 to April 1979.

Table A-3. Field Test Results of User Equipment Navigation Accuracy

	Position Accuracy (M)		Velocity Accuracy (M/S)	
	50%	90%	50%	90%
Four Channel IMU-Aided Set	10	18	0.3	0.7
Four Channel Unaided Set	10	16	0.6	2.5
Single Channel P-Code Set	14	27	1.4	3.7
Single Channel C/A Code Set	16	37	0.7	3.7
Manpack, Static	13	28	0.2	0.7

One of the unexpected results of the field testing is that the Z-Set accuracy is better than anticipated. This result prompted a decison by DoD to "corrupt" the C/A signal in the operational GPS to limit navigation accuracy to approximately 500 meters (3-D, RMS) in early operations.

Z-Set Performance

Z-Set field test results are shown in Figure A-4. The accuracy of a C/A signal set demonstrated remarkable performance. Also shown is the ability to navigate with three satellites coupled with altitude as the fourth input. This would imply that civil use can become widespread as soon as 3 satellites are in view most of the time. The coverage could occur as early as late 1985.

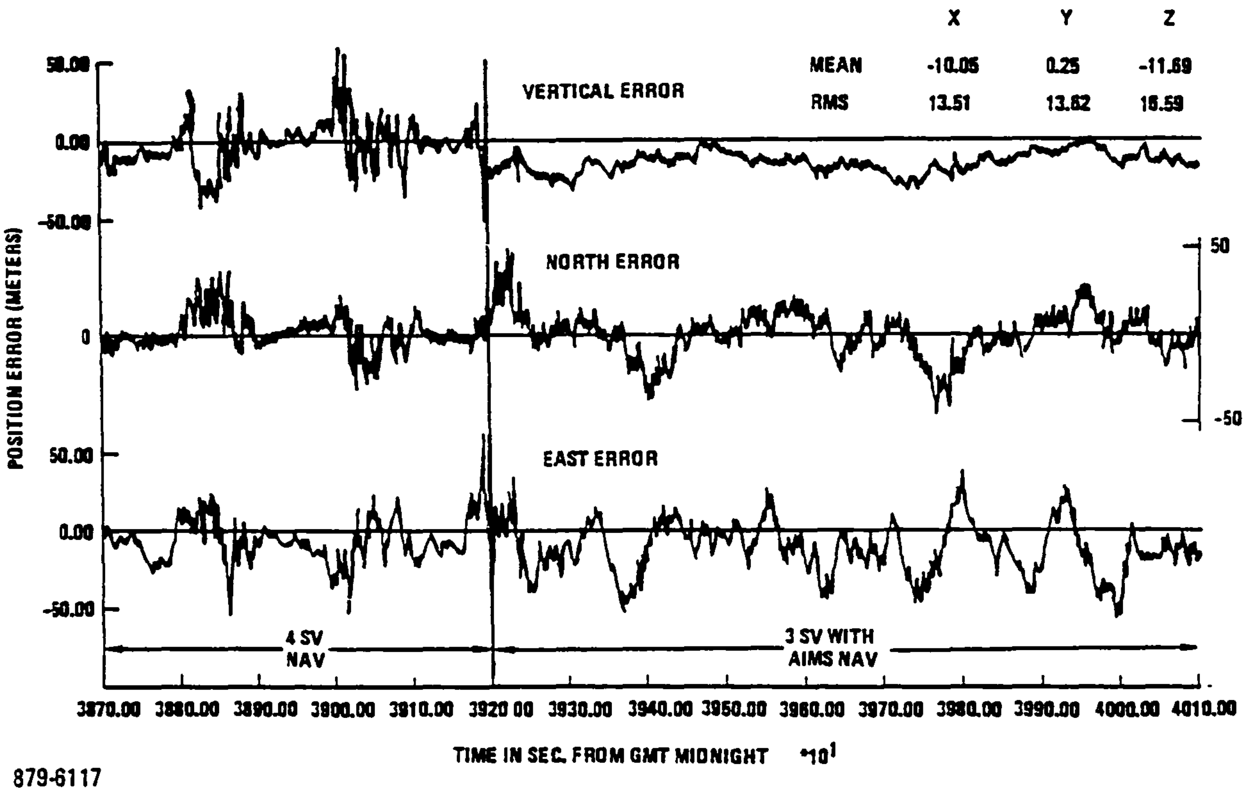

Figure A-4. Z-Set Field Test Results – Position Errors, April 4, 1979, C-141 Racetrack Course at Yuma, AZ.

Landing Approaches

GPS sets have the capability for operator entry of 3-D waypoints into computer memory so that steering information (range, bearing and time-to-go) can be computed from one waypoint to the next. The X-Set, in particular, uses this information to drive a Pilot Steering Display (PSD) which displays horizontal and vertical deviation from the intended flight path between waypoints. If key landing approach points are entered as NAVSTAR waypoints, the pilot is provided with a self-contained, landing-approach instrumentation system which is independent of ground controllers or equipment.

Tests in a UH1 helicopter demonstrating landing approaches were conducted at the Yuma Test Range and results are shown in Figure A-5. Note that all test approaches penetrated an imaginary Intrument Landing System (ILS) window at decision height. Conclusions from the test program are:

- Current GPS accuracies are adequate to steer aircraft on non-precision type (Tacan, Vor, ASR) approaches to landing.
- Pilot can execute an approach independent of ground control and ground equipment, provided he knows coordinates and altitudes of key approach points.
- Studies show that a GPS set at the runway with a data link to the GPS-equipped aircraft will eliminate several system errors (ephemeris, clock, atmosphere) and permit precision type (ILS, MLS, PAR) approaches to landing.

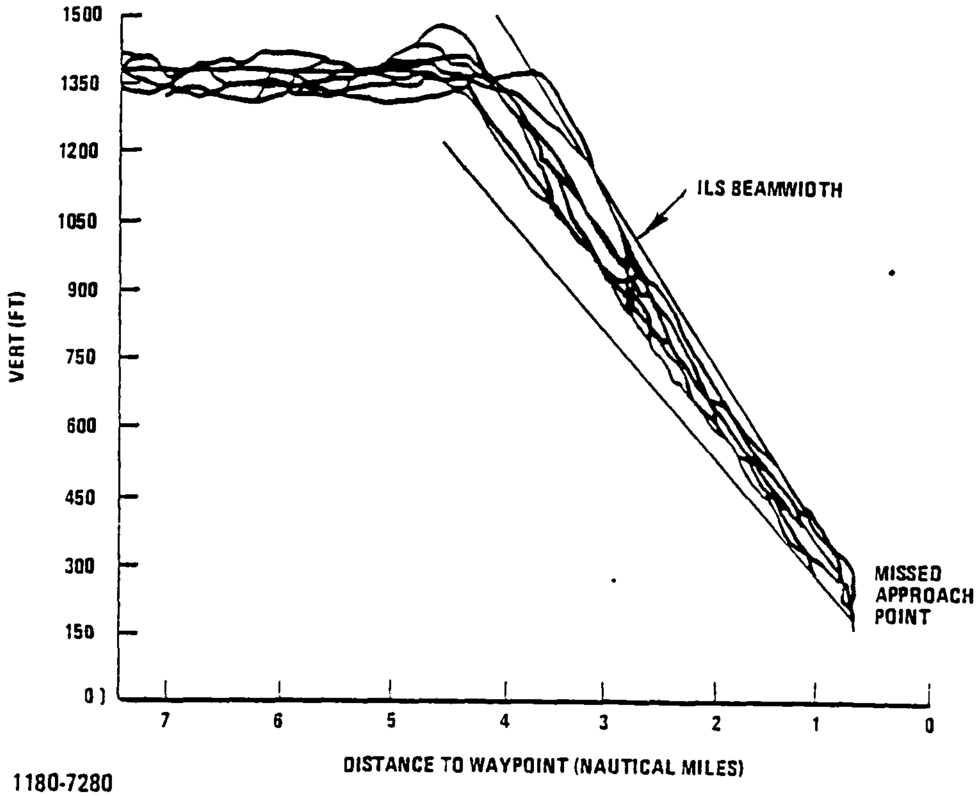

Figure A-5. UH1 Landing Approach with a NAVSTAR X-Set and PSD

Rotor Modulation

In November of 1978, UH1 rotor modulation tests were conducted at the Yuma Test Range in a scenario depicted by Figure A-6.

An X-Set antenna was located at positions 6-20 feet from the rotor shaft and GPS signals were received through the spinning rotor. Modulation effects from the rotor resulted in a net power increase in the received GPS signal and a 2-10 dB variation in the received signal/noise ratio. No navigation performance degradation was detected.

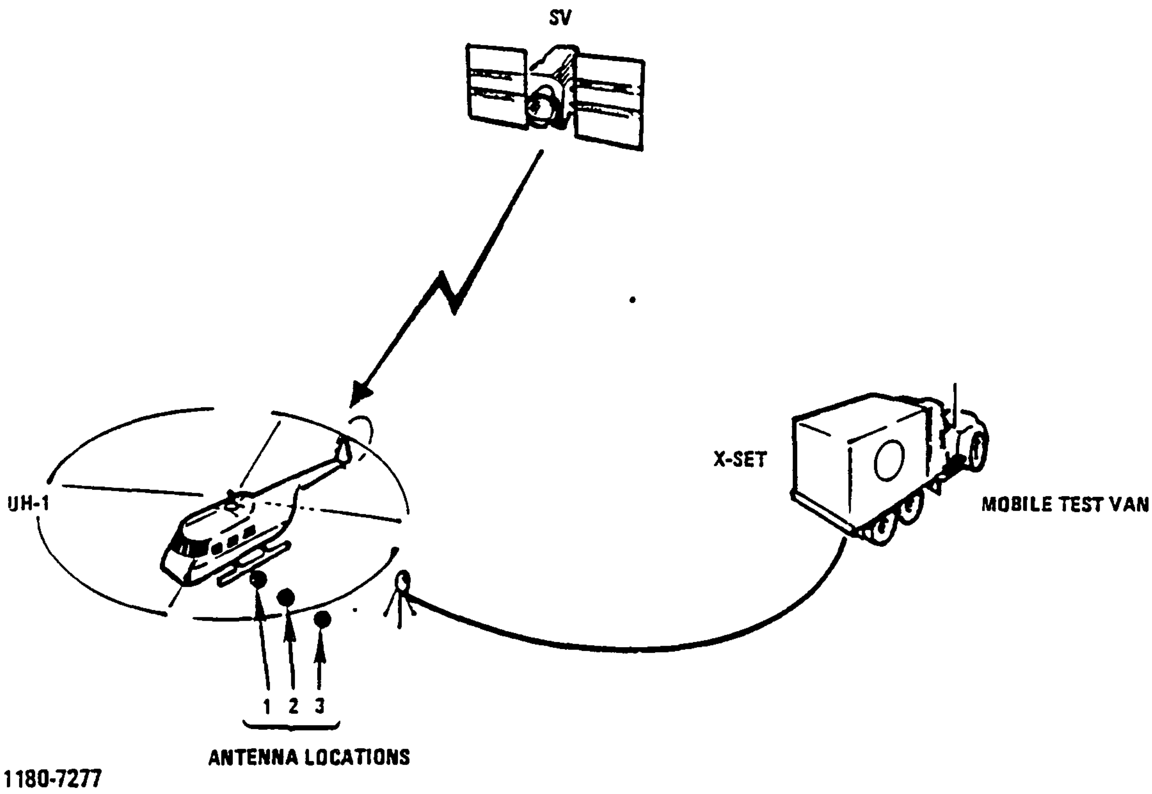

Figure A-6. UH1 Rotor Modulation Test Scenario

Foliage Attenuation

In December 1978 the U.S. Army conducted qualitative foliage attenuation testing in light-to-medium foliage at Elgin Air Force Base. The ability of the Manpack to obtain a static fix at a surveyed position was assessed as a function of satellite elevation. It was generally found that the Manpack had no difficulties with satellites at or above twenty degrees of elevation. A "rule of thumb" that seemed to emerge from the testing is the GPS signals can be received under foliage through which some sky is visible.

Differential GPS

The need to provide a higher degree of accuracy for precision approaches than that available from GPS led to the concept of differential navigation.

In this concept, a GPS receiver is located on a surveyed point where X, Y and Z system errors can be identified and corrections determined. These corrections are data linked to aircraft which operate in the same geographical area and are, therefore, subject to the same errors. The X, Y and Z corrections obtained from the reference receiver are combined with the aircraft receiver solution thereby improving the position accuracy of the aircraft navigation solution.

Results of differential navigation tests at Yuma in January 1980 are shown in Table A-4. As noted on the chart, regardless of the magnitude of the GPS system error, the corrected solution error was less than three meters in the X, Y and Z axes.

Table A-4. Differential GPS Test Results

Position	Uncorrected Error (M)	Corrected Error (M)
X	28	2.6
Y	21	2.7
Z	11	2.7

APPENDIX B

DIFFERENTIAL GSP COMPUTER SIMULATION

APPENDIX B

DIFFERENTIAL GPS COMPUTER SIMULATION

1. INTRODUCTION

This memo includes results of computer runs which simulate differential GPS for civil applications. Though they are preliminary, the results indicate that the differential GPS concept is promising and warrants additional study.

The simulation extends over a 2000-second interval. The user is assumed stationary for 1000 seconds. Then, the user takes off, maneuvers to straight flight, and makes touchdown 560 seconds later. Flight dynamics include maximum accelerations of 0.2g and maximum velocities of 200 nmi. per hour. This simple flight pattern is intended to check the performance of the Kalman filter employed. A four channel (non-sequencing) receiver operating with a 1.2 second cycle time is assumed for both the user and the calibration site..

2. DIFFERENTIAL GPS

As shown in Figure B-1, the user observes four pseudoranges, R_1, R_2, R_3, R_4; four delta-ranges, ΔR_1, ΔR_2, ΔR_3, ΔR_4 directly from the satellites and four range differences, Q_1, Q_2, Q_3 and Q_4 transmitted from the GPS calibration site whose location is known on the ground.

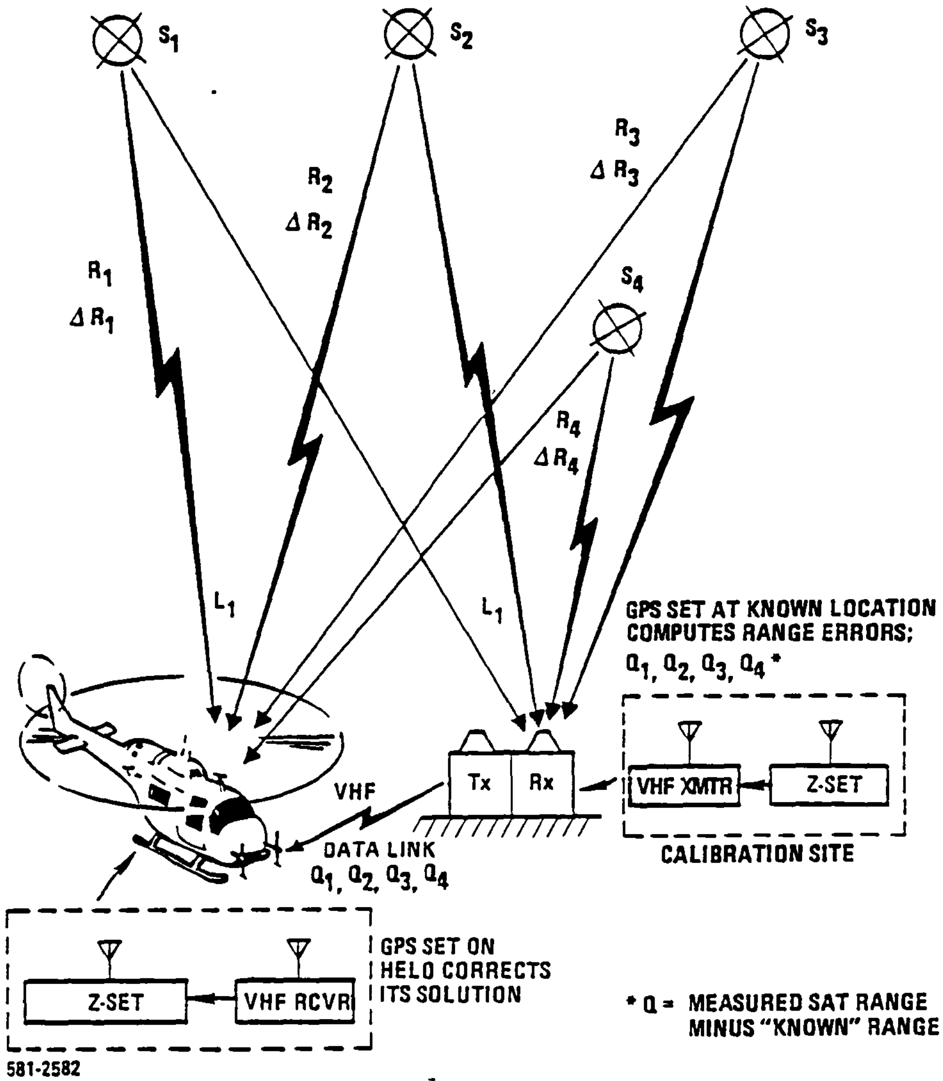

Figure B-1. Differential GPS Concept Under Consideration

3. SIMULATION PROGRAM

Magnavox has developed a computer simulation program for NAVSTAR GPS navigation which is adaptable to a differential GPS system. In the development of the simulation program a family of subroutines has been written to facilitate development of the main program. Usage of proven sub-programs stored as an auxiliary file enhances compiling and editing the main routine. A list of these sub-programs with a brief description is tabulated in Table B-1. Figure B-2 is the program flow chart. Table B-2 summarizes the errors applied in the simulation. Time constants, τ, are typical for random error sources normally encountered. The time constant for the hypothetical signal degradation noise source was arbitrarily assumed equal to that used in Reference 1.

4. SIMULATION RESULTS

Tables B-3 and B-4 summarize conventional and differential GPS performance for the P Code, C/A Code and degraded C/A Code. Figures B-3 through B-8 show performance versus time for the cases summarized in Tables B-3 and B-4.

Table B-1. Subroutines

1.	SATDT	A subroutine used to open, read, and close the satellite ephemeris data file, and call for the ECEF coordinate calculation at time, T.
2.	SATGN	A subroutine intended to determine the x, y, and z ECEF coordinates of any designated satellite at time T from the ephemeris data.
3.	NSAT	A subroutine that cycles through the ECEF coordinates of all the satellites, calculating their elevation angles, and tabulates all those that have an elevation angle higher than the masking angle.
4.	PRFGN	A subroutine intended to generate a mission profile.
5.	COTRN	A subroutine for converting from latitude, longitude, and altitude inputs to x, y, and z Earth Centered Earth Fixed (EDEF) cartesian coordinates, and the reverse conversion.
6.	GPRT	A subroutine for data printout in a report format on logical unit 2 (LU2) when called.
7.	GDOPF	A function subprogram which calculates the "Geometric Dilution of Precision" (GDOP) from the user coordinates and four sets of satellite ECEF coordinates.
8.	SATSL	A subroutine which sorts through all combinations, taken four at a time, of satellites above the masking angle, finding the GDOP and listing the combination of four which has the least value of GDOP.
9.	RANGE	A subroutine that calculates the observed range from the user to each satellite and adds error terms to produce the observed range containing the anticipated random errors.
10.	NAVGN	A subroutine which calculates user position and clock error ECEF cartesian coordinates from four sets of satellite ECEF coordinates and their respective ranges.
11.	GPRT1	A subroutine used for data printout. This is the time and rms error. The printout may, on command, be either simple listing, or graphical. If graphical, at time T=0, the subroutine provides the coding for scaling, labeling, and drawing the axes and for input data printout.
12.	HMTRX	A subroutine to set up the conditional elements of the 12 x 15 Hm Transfer Matrix, along with the directional cosines for the H matrix and its inverse, the G matrix.
13.	KALM	A subroutine constituting the Kalman filter. With an optional input command, the contents of the various vectors and matrices are dumped for each time increment.

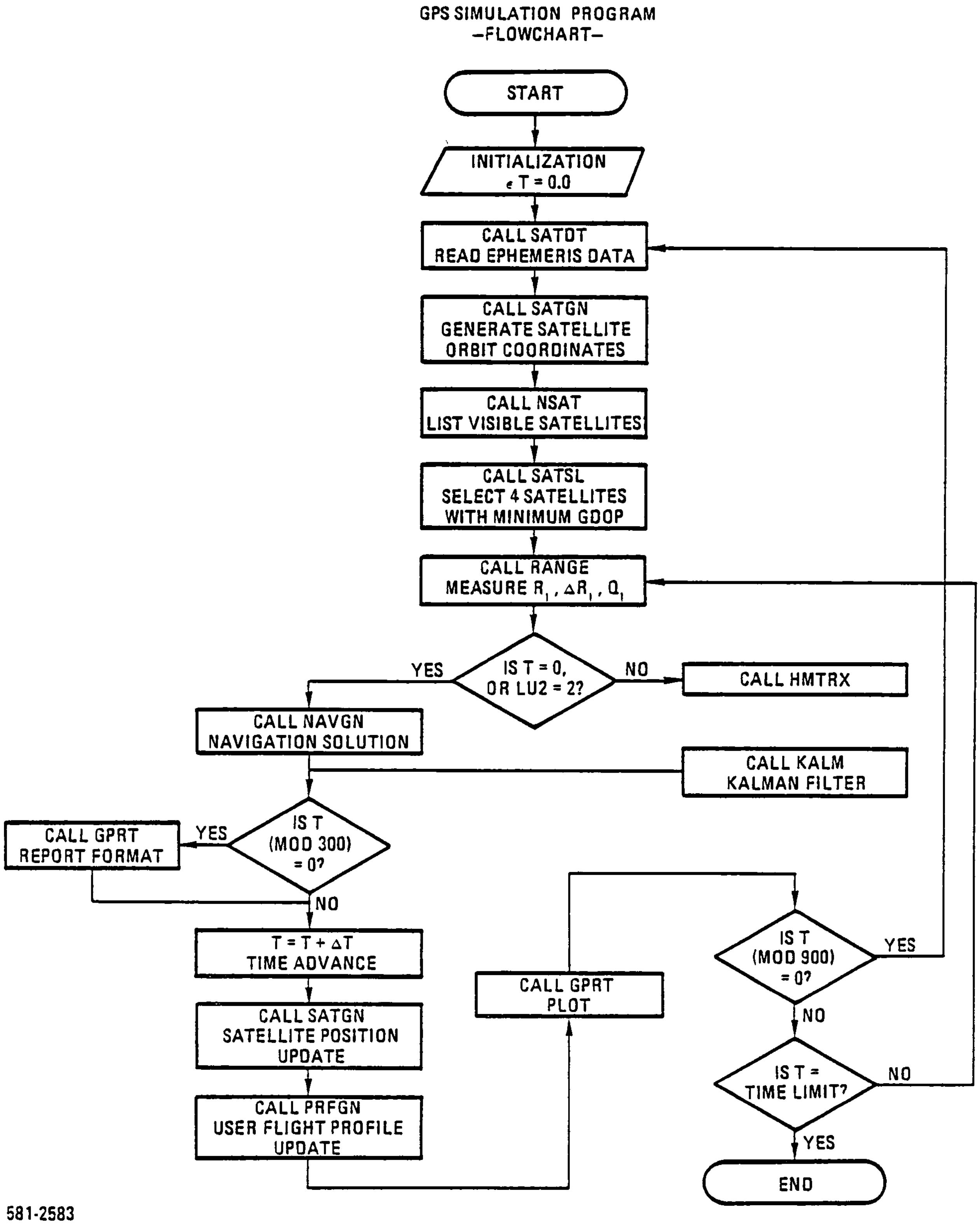

Figure B-2. Flow Chart.

Table B-2. Error Source Summary

Source	C/A-Code	P-Code	Remarks
1. Satellite Ephemeris	3.5 m Bias		
2. Degradation	UERE = 80 m, τ = 30 min, MP		SIGS = 80, SRN(I,1)
3. Receiver Noise (Pseudorange Noise and Range Mechanization Error)	SIGN = 10 m, WG	SIGN = 1.5 m	
4. Delta-Range Measurement Error	$\sigma_{\Delta}R$ = 0.02 m, WG		RES(1,9)
5. Ionospheric Delay Error	SIGI = 3.0 m τ = 30 min, MP	SIGI = 1.0 m	SPN(I,4)
6. Tropospheric Delay Error	SIGT = 1.5 m τ = 2 hrs, MP		
7. User Clock Bias	1° rms/sec, SIGB = 0.0815, RW, SIGB x $\sqrt{DT}$, 1.5 m Bias		SIGB
8. User Oscillator Frequency Offset	$\Delta F/F$ = 1E-10, Exponentially Correlated, BDOT = 0.03, τ = 6400, 1 m Bias		BDOT
9. Differential Range Error	$\sigma_{diff.R}$ = d x 1E-4		d = distance between user and G/S (RES(1,2))
10. Ground Station Mechanization Error	σ_M = 0.1 x SIGN		
11. Multipath	σ_m = 1.0 m, τ= 10 min, MP		SIGR, SRN(I,2) Ground Station only

*Same as the C/A-Code case unless otherwise noted.

Table B-3. Single Axis Position Errors, Conventional Mode

Statistical Parameter*	P Code Single Axis Errors (Meters)			C/A Code Single Axis Errors (Meters)			Degraded C/A Code Single Axis Errors (Meters)		
	x-axis	y-axis	z-axis	x-axis	y-axis	z-axis	x-axis	y-axis	z-axis
Mean**	-9.93	2.66	-8.52	-13.5	3.98	-10.6	-82.2	-52.3	172
1σ Value	10.1	3.13	8.71	15.3	6.22	11.1	83.0	52.6	173
2σ Value	20.2	6.26	17.42	30.6	12.44	22.2	166.0	105.2	346

*Errors are evaluated at the moment of user touchdown.
**Mean over 100 computations.

Table B-4. Single Axis Position Errors, Differential Mode

Statistical Parameter*	P Code Single Axis Errors (Meters)			C/A Code Single Axis Errors (Meters)			Degraded C/A Code Single Axis Errors (Meters)		
	x-axis	y-axis	z-axis	x-axis	y-axis	z-axis	x-axis	y-axis	z-axis
Mean**	-0.438	-0.113	.236	-1.92	0.175	-0.201	-3.29	-.0291	-1.02
1σ Value	1.28	0.826	.694	6.51	4.34	2.56	7.38	4.18	3.15
2σ Value	2.56	1.652	1.388	13.01	8.68	5.12	14.76	8.36	6.30

*Errors are evaluated at the moment of user touchdown.
**Mean over 100 computations.

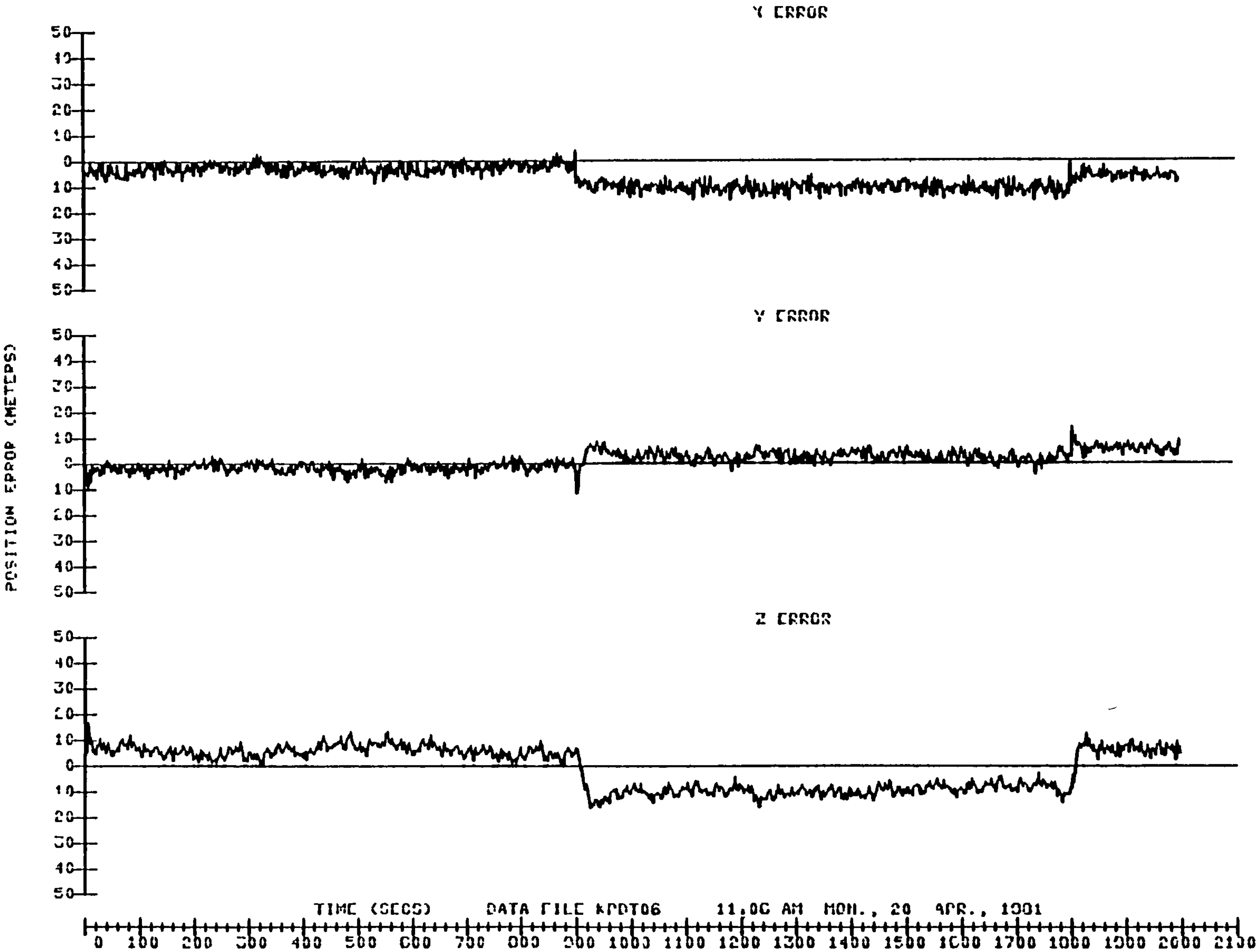

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Figure B-3. Conventional P Code Performance

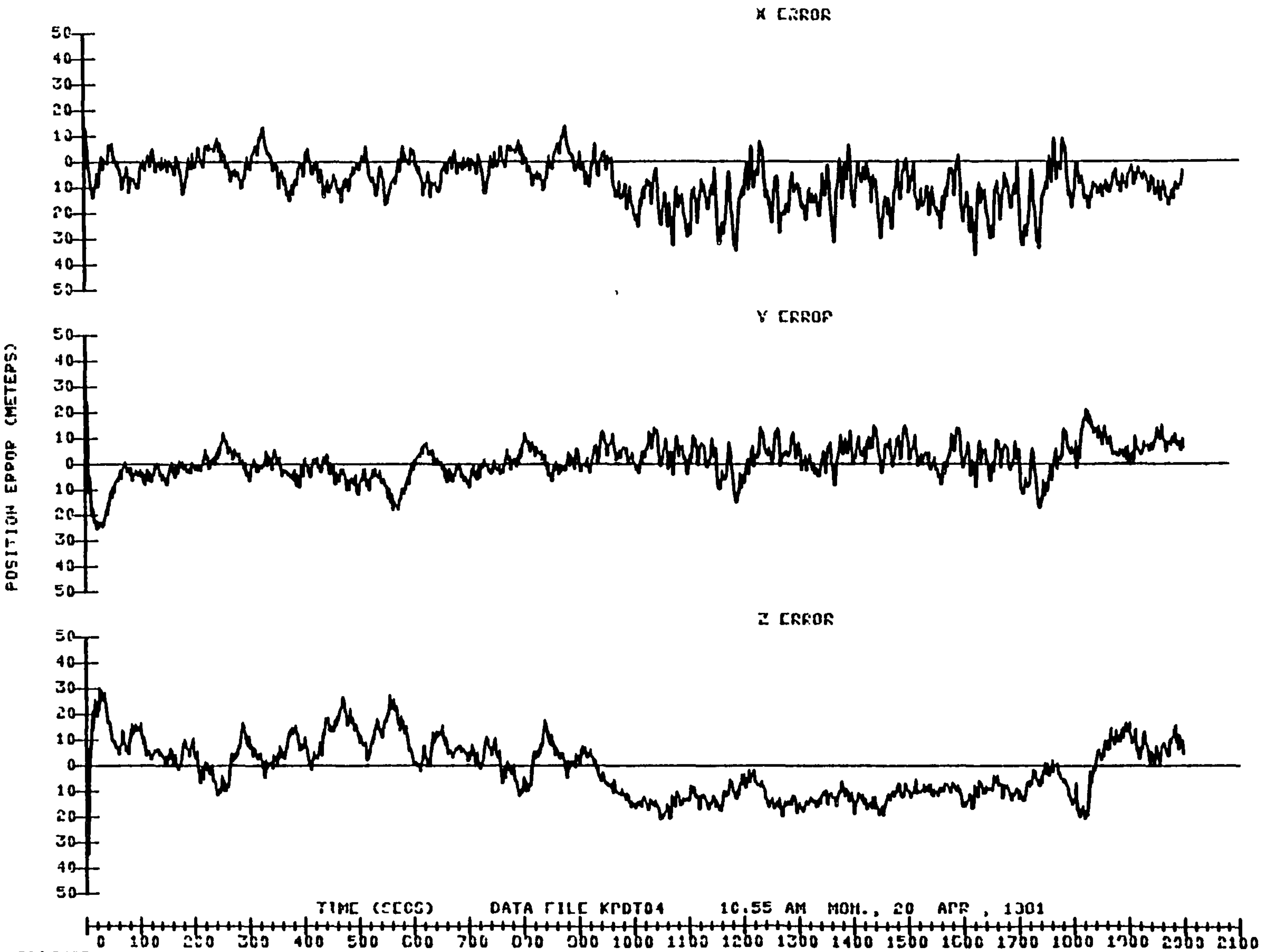

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Figure B-4. Conventional C/A Code Performance

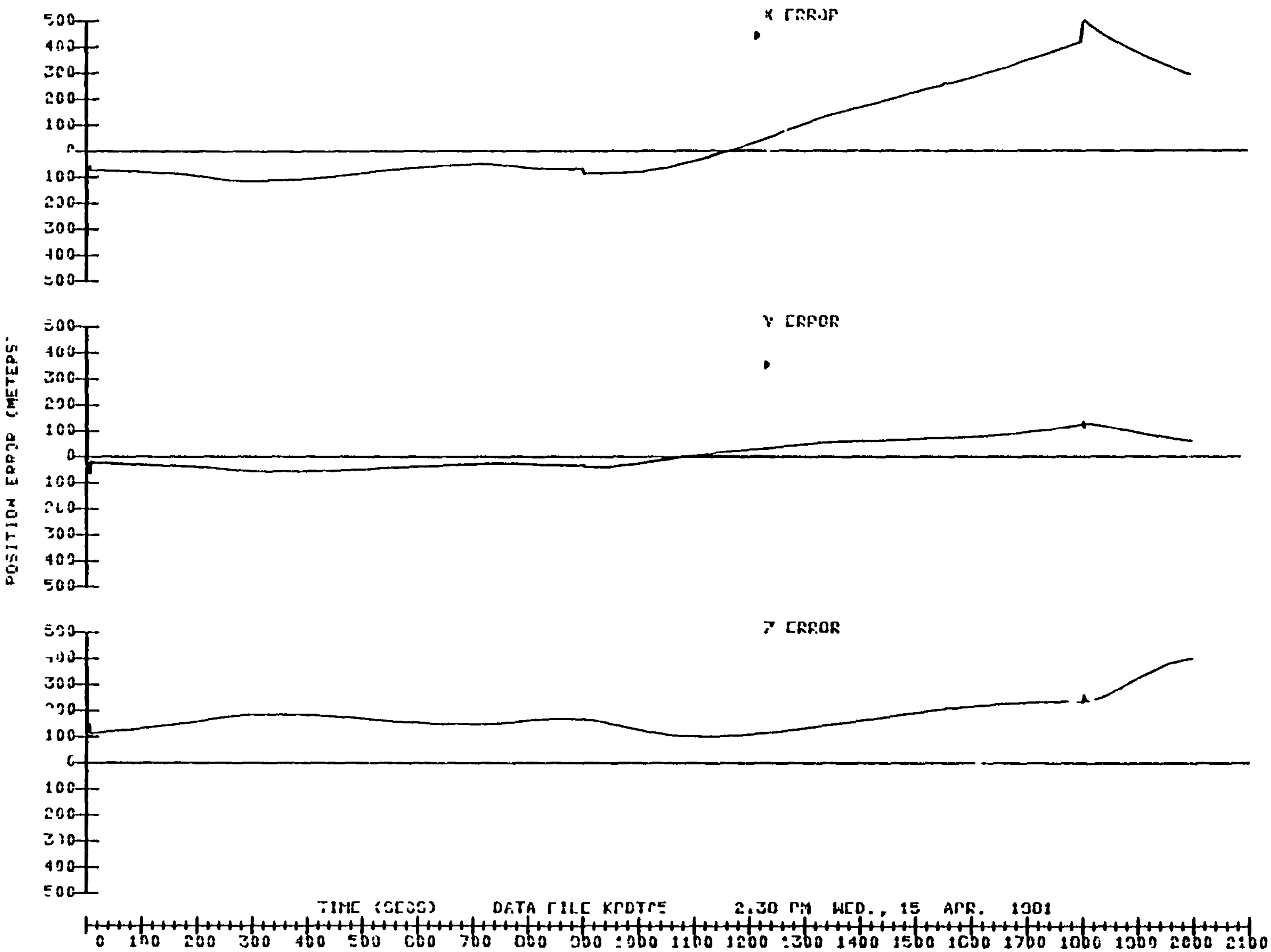

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Figure B-5. Conventional Degraded C/A Code Performance

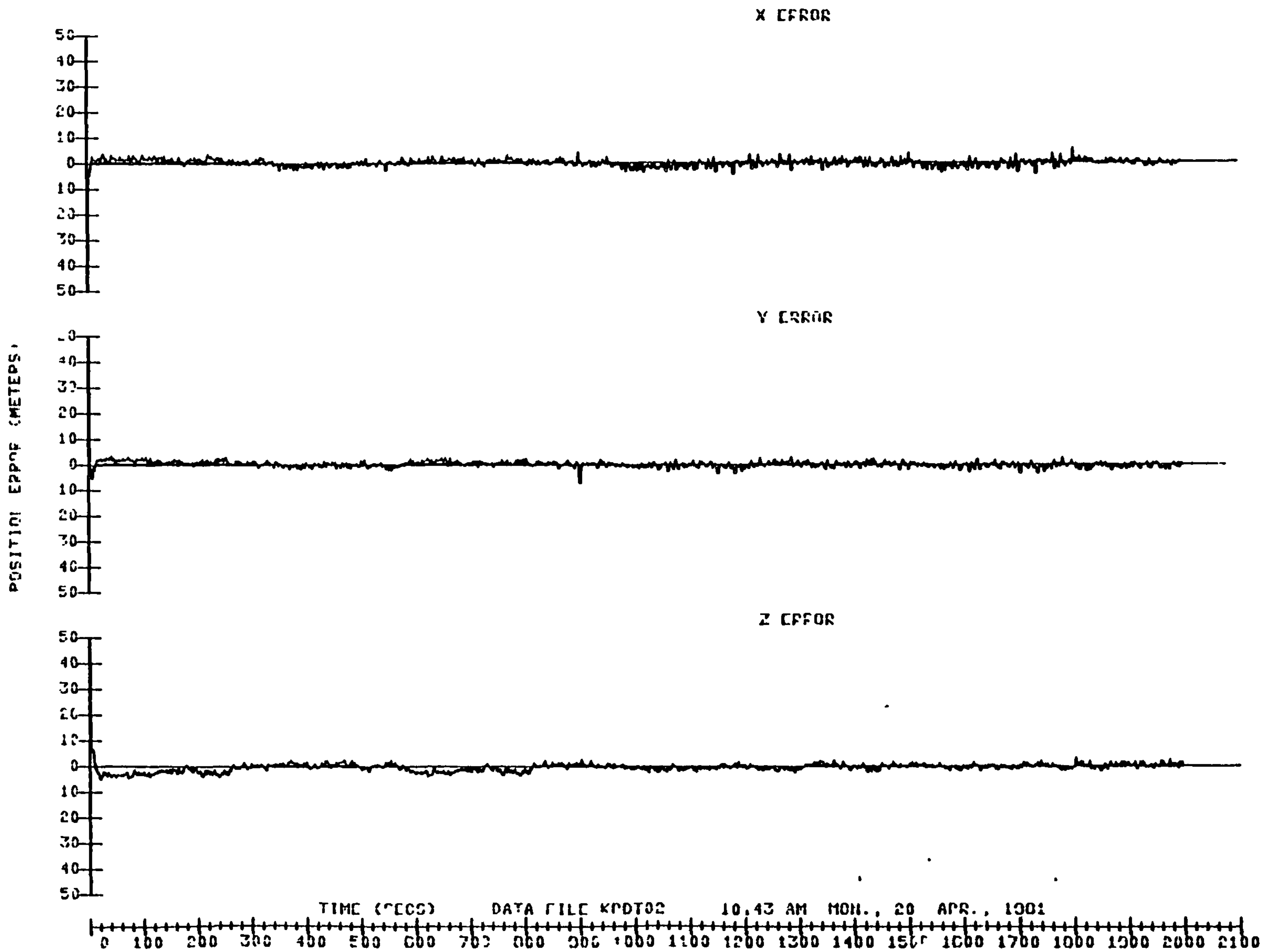

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Figure B-6. Differential P Code Performance

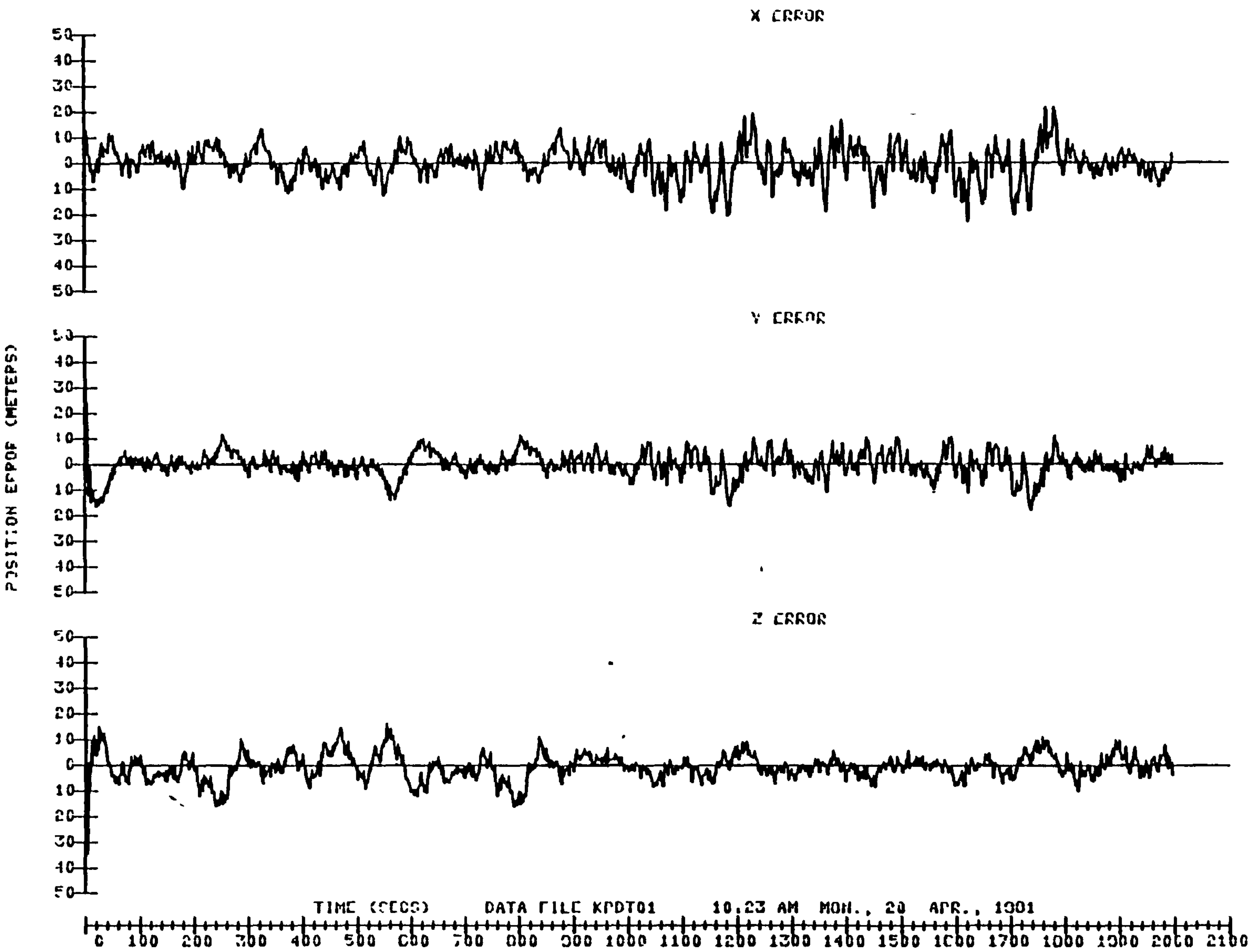

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Figure B-7. Differential C/A Code Performance

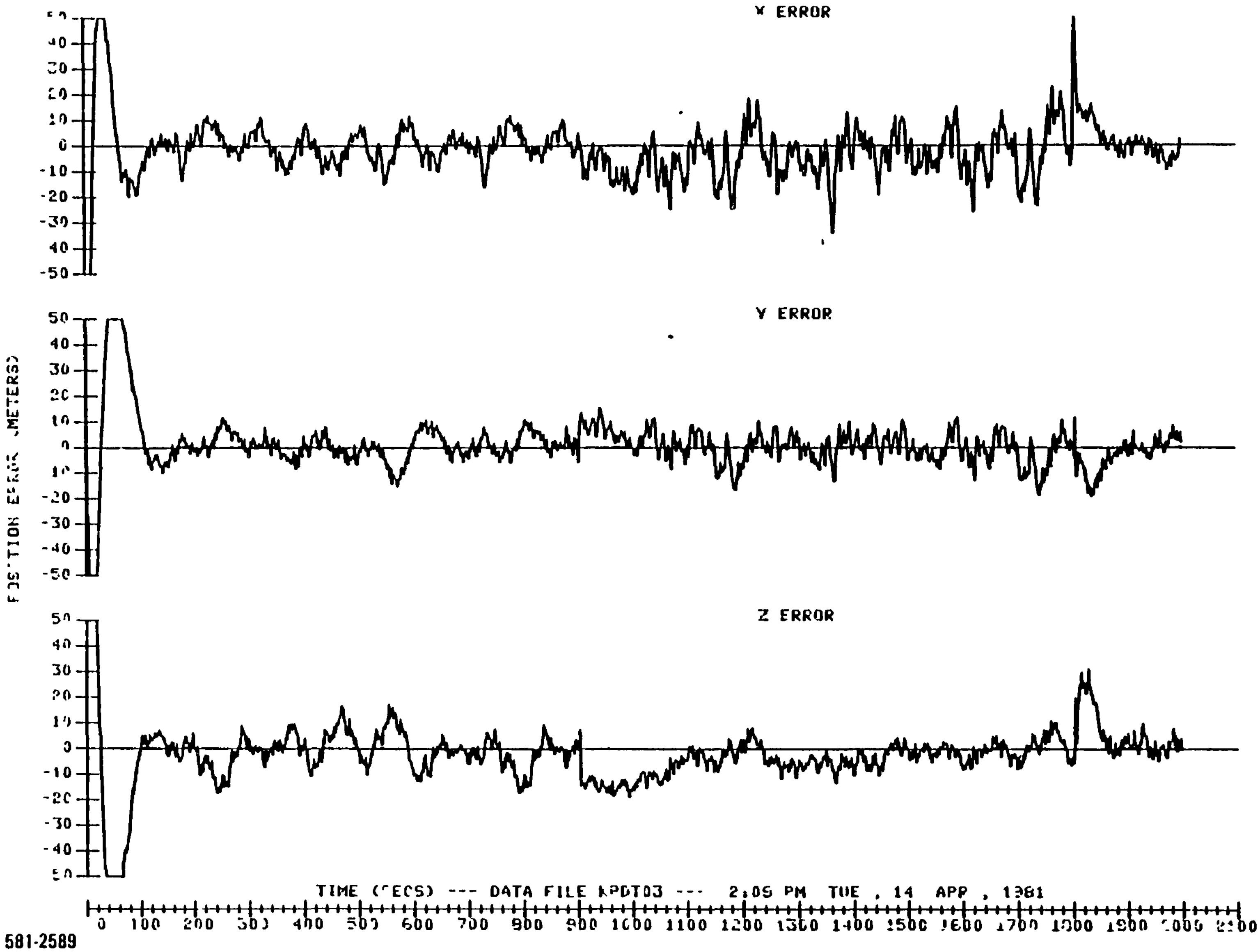

Figure B-8. Differential Degraded C/A Code Performance

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16 Abstract

The Global Positioning System (GPS) and its potential for area navigation, landing, and takeoff under minimum ceiling and advanced air traffic control operation is discussed. The following topics are reported: status of the GPS system; GPS signal availability for civil community; alternative differential GPS concepts; predicted performance enhancement achievable with differential GPS and the operational improvements which will result; and a development program to test and evaluate differential GPS concepts, performance and operational procedures applicable to helicopters. Potential benefits which will be derived from helicopter use of GPS in the differential mode are identified.

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